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JANNE KINNUNEN
VERIFICATION OF A VEHICLE NAVIGATION SYSTEM

Master of Science thesis

Examiner: Dr. Jussi Collin
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ABSTRACT

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An autonomous vehicle needs a navigation system in order to operate safely. The navigation system that is used in autonomous vehicle needs to have enough accuracy to ensure safe operation. Because of this, it is vital that system can be verified before its taken in production use. In the worst case a system that is not functioning correctly can cause massive damages.

The background for this thesis is a project to develop an industrial vehicle navigation system. The navigation system must be able to provide a reliable and accurate position, allowing the autonomous vehicles to operate without human interaction. The client had an existing navigation system that the new system replaced.

The verification required different platforms that allowed comprehensive and safe testing during the development process. In this project, the platforms included simulation, a smaller indoor testing vehicle, and a full size vehicle. The simulation provided a controllable, fast, and repeatable platform for the testing. The indoor testing vehicle allowed safe testing in the office. The full size vehicle acted as a final verification platform that represented a production environment.

Besides the platforms, methods utilizing them are needed in the verification. The methods introduced in this thesis are straight line driving, loop completion, and absolute measurement tracking. Additionally, the new system is compared against the old existing system.

TIIVISTELMÄ

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Autonominen ajoneuvo tarvitsee navigointijärjestelmän toimiakseen turvallisesti. Navigointijärjestelmän tulee kyetä määrittämään ajoneuvon sijainti riittävän tarkasti, jotta turvallinen automaattiajo olisi mahdollista. Tämän takia on erityisen tärkeää kyetä varmentamaan järjestelmän toiminta etukäteen ennen kuin se laitetaan tuotantoympäristöön. Pahimmassa tapauksessa huonosti toimiva navigointijärjestelmä voi aiheuttaa mittavia vahinkoja.

Tämän diplomityön taustana on asiakasyrityksen tarve kaupalliselle navigointijärjestelmälle. Järjestelmän tulee kyetä navigointiin tarkasti ja luotettavasti, jotta autonomisesti liikkuvat koneet voivat toimia ilman ihmisen avustusta. Asiakkaalla oli jo ennestään olemassa navigointijärjestelmä, jonka uusi järjestelmä korvasi.

Verfiointiin tarvitaan erilaisia alustoja, jotka mahdollistavat kattavan ja turvallisen testauksen kehityksen eri vaiheissa. Tässä projektissa käytetyt alustat olivat simulointi, sisäkäyttöön soveltuva testiajoneuvo ja varsinainen täysikokoinen ajoneuvo. Simulaatio tarjoaa hallittavan, nopean ja toistettavan alustan testaukseen. Sisäkäyttöön soveltuva testiajoneuvo mahdollistaa turvallisen testauksen toimistoympäristössä. Varsinaisella lopullisella ajoneuvolla varmistetaan järjestelmän toiminta oikeassa ympäristössä.

Alustojen lisäksi tarvitaan menetelmiä, joita käytetään varmentamisessa. Näistä menetelmistä käsitellaan suoraan ajaminen, suljetun silmukan ajaminen ja absoluuttisten mittausten seuranta. Lisäksi uutta järjestelmää verrataan vanhaan olemassa olevaan järjestelmään.

PREFACE

This thesis was written at Atostek Oy and its background is an industrial application. I would like to thank Atostek for the subject and financial support for this thesis. I would also like to thank our customer for allowing me to write about the subject.

I would like to thank my thesis examiner Dr. Jussi Collin for his guidance and expertise on the subject and Dr. Juhana Helovuo, who gave me excellent guidance and valuable feedback. Special thanks go to my parents for supporting me during my Master's degree studies.

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Janne Kinnunen

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND SYMBOLS

AGV	Automated guided vehicle
CAN	Controller Area Network
DGNSS	Differential GNSS
FOC	Full operational capability
GLONASS	Global’naya Navigatsionnaya Sputnikovaya Sistema
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GUI	Graphical user interface
IMU	Inertial measurement unit
IoT	Internet of Things
LSB	Least Significant Bit
IRNSS	Indian Regional Navigation Satellite System
MEMS	Microelectromechanical systems
PPS	Precise positioning service
QZSS	Quasi-Zenith Satellite System
RTK	Real time kinematic
SA	Selective availability
Satnav	Satellite navigation
SPS	Standard positioning service
VBA	Vibrating-beam accelerometer
VNS	Vehicle navigation system
WLAN	Wireless local area network

e	measurement error
Y	transfer function
s	stimulus
k	power factor
A, B and C	transfer function parameters
C_α	Cornering stiffness coefficient

1. INTRODUCTION

The development and continuous advancement of automation and internet of things (IoT) has increased the need for automatic vehicle navigation systems (VNS). For a vehicle to be automated, in most cases, its location has to be known. IoT, on the other hand, has brought computers into machines where they have not previously been, and introduced a possibility for location tracking. Automated machines can be found at factories, where they are used move heavy objects, warehouses use small automated vehicles to move boxes, and ports handle container moving with automated machines. Location tracking is used, for example, in city busses to provide real-time location information for commuters. Delivery services can track the locations of their vehicle fleet. While all these vehicle navigation systems can be implemented using numerous of different technologies, and the accuracy required from these can vary greatly, all of them share one common requirement about accuracy or correctness of the system. A navigation system that can not provide location that is accurate enough is useless in operation.

Before a vehicle navigation system can be put to production environment it has to be verified. The aim of this thesis is to provide methods how to verify the correctness of a VNS. The foundation of this thesis is in the development of a real vehicle navigation system of an automated guided vehicle (AGV) for an industrial application. The goal of the project was to replace an existing navigation system, which allowed comparison to it while developing the new system. The system requires high accuracy in order the operate properly. This requirement demanded sufficient verification before the system could be put in to operation.

This thesis is divided into seven chapters. Chapter 2 introduces vehicle navigation systems. The chapter discusses the need for navigation systems and shows examples of such systems. Chapter 3 looks into measurement concepts and why they affect the design of navigation systems, and into choosing proper sensors. In Chapter 4, different types of sensors used in modern navigation systems are introduced in detail. The chapter gives examples of sensors, how they work, and how each sensor can be used in navigation. Chapter 5 outlines different platforms on which a vehicle navigation system can be tested and verified. The chapter starts with software simulation and finishes with full scale vehicles. In Chapter 6, methods on how the testing and verification can be done are provided. It also shows examples how these methods were used in developing a real vehicle navigation system. Finally, Chapter 7 summarizes the results obtained in this thesis.

2. VEHICLE NAVIGATION SYSTEMS

The Oxford Dictionary of English defines *navigation* as "The process or activity of accurately ascertaining one's position and planning and following a route" [1]. The definition contains three separate actions. First action is finding the position. The second and third are figuring out a sensible route and guidance i.e. making decisions where to go according to the position and route. The scope of this thesis is only the position finding, and how to verify the correctness of it. Navigation has existed over centuries, but in the recent past advancements in computer and sensor technologies have allowed the development of vehicle navigation systems. An autonomous vehicle requires a real-time navigation system, which requires a fast computer. Size of the computer must also be small enough. Sensors need to be small and accurate in order to be useful in vehicle navigation. The cost of the computers and sensors has also decreased significantly, making it possible the use navigation in a greater number of applications than before.

A vehicle navigation system has one task, which is the reporting of the position and velocity of the vehicle it is attached to. It may also report the attitude, or at least the heading, angular rate, and acceleration of the vehicle, depending on the system requirements. A navigation system consists of navigation sensors and a navigation software computer. A navigation sensor is a device measuring some quantity and reporting it the navigation software. In this project, the navigation sensors included gyroscopes, accelerometers, wheel encoders, steering encoders, satellite navigation receivers, and marker detection sensors. Other sensors, such as radio transponders and radars, were addressed but not used. Different sensors will be discussed in chapter 4. Navigation software receives measurements from a number of sensors and uses navigation algorithms to deduce the navigation solution or result. At minimum, the solution must include x- and y-coordinates with respect to some known coordinate system. Usually, the solution will also include the heading of the vehicle. A navigation system may be implemented as an onboard system, where it will be located on the vehicle, or as an external system, where the navigation is done elsewhere. Figure 2.1 shows a simplified architecture of a vehicle navigation system.

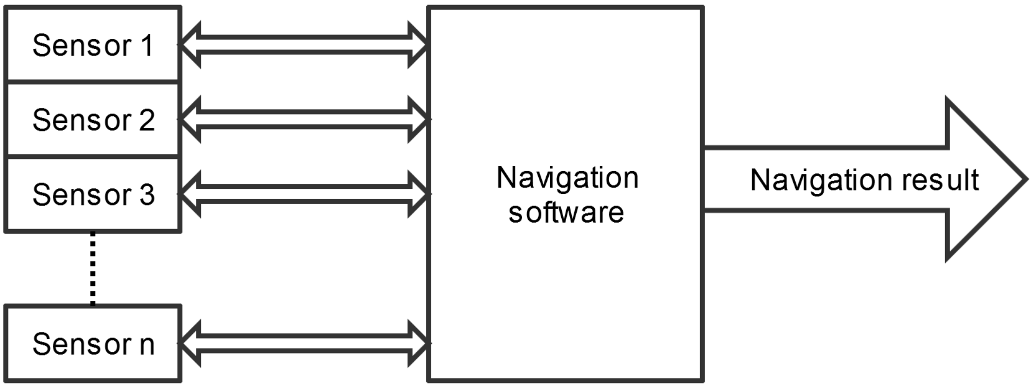

Figure 2.1 *Vehicle navigation system architecture*

Figure 2.2 shows an example data flow of a fully featured vehicle navigation system. The system has two absolute measurement sensors. Those sensors are discussed more detailed in section 4.2. GNSS sensor allows position initialisation and recovery, but it is not used in real-time navigation. Marker detection ensures that the position remains accurate, as navigation by relative sensors is not accurate enough over longer periods. Continuous real-time navigation is achieved by wheel and steering encoders and inertial sensors. All these sensors together with the navigation software are capable of implementing an accurate and robust vehicle navigation system.

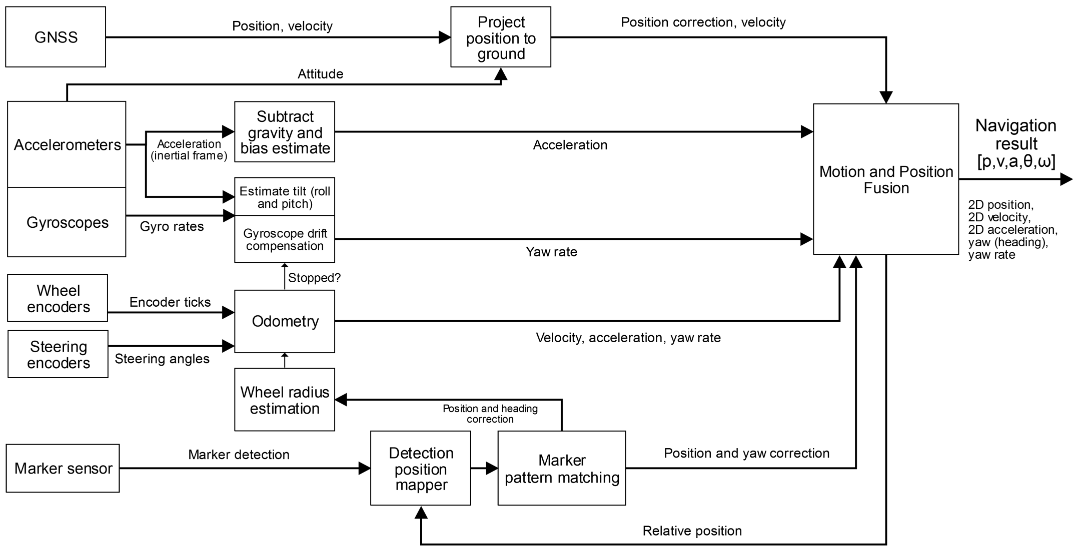

Figure 2.2 *Vehicle navigation system data flow*

3. MEASUREMENT CONCEPTS

A sensor is a device that gathers the information of the physical world and transforms that information into an electrical signal. The information gathered is called a stimulus or a measurand. In an ideal world with ideal sensors, a stimulus would always result in the same electrical signal which would represent the real value of the physical world. However, sensors are not ideal and all of them exhibit some amount of error. Error is defined as the deviation from the expected ideal value:

$$e = measurement - actual, \tag{3.1}$$

where e denotes the error in the measurement, *measurement* is the value that the sensor reported, and *actual* is the real physical value of the quantity being measured. Variations in materials and manufacturing cause errors. A bad design of the sensor itself can also lead to a significant source of error. Changes in the environment for example temperature, pressure, and humidity may affect the performance of the sensor. In this chapter measurement concepts are discussed and how they affect the difference between real and measured value [39].

3.1 Transfer function and sensitivity

Each sensor has a relationship between the measured stimulus and the final output. This relationship is called a transfer function. Transfer function describes how the measured value can be translated to the output of the sensor. The simplest transfer function is a linear equation:

$$Y = A + Bs, \tag{3.2}$$

where Y is the output of the sensor, A is a constant offset or a zero input value,

B is the slope of the linear function and s is the measured stimulus. Ideally, the transfer function would be correct always and did not include errors. However, each sensor and measurement contains several sources of errors and therefore the transfer function is always only an approximation of the real measured value. While a sensor can have linear transfer function often this is not the case. Transfer functions may be logarithmic, exponential, power, or polynomial functions:

$$Y = A + B\ln(s), \tag{3.3}$$

$$Y = Ae^{ks}, \tag{3.4}$$

$$Y = A + Bs^k, \tag{3.5}$$

$$Y = As^2 + Bs + C, \tag{3.6}$$

where A, B, and C are parameters and k is the power factor.

Parameter B in Equation 3.2 is called *sensitivity*. For a linear transfer function sensitivity is a single value. A non-linear transfer function can have different sensitivities depending on the measured stimulus. Sensitivity describes how much the sensor output reacts to changes in the stimulus.

3.2 Accuracy

Accuracy is one of the most important concepts when discussing sensors and measurements. It can also be referred as inaccuracy, but both terms have the same basic meaning. Accuracy or inaccuracy tells us how much can the measured output value deviate from the actual physical value that is being measured. When designing vehicle navigation systems, the accuracy of each sensor has to be taken in to consideration, and how it will affect the final accuracy of the system. Every measurement, no matter how accurate, needs to be given with an uncertainty, in order to be considered a complete measurement [35]. See Table 3.1 for an example of inertial measurement unit specifications.

Table 3.1 *Example characteristics of an inertial measurement unit [7]*

Sensor	Accelererometer	Gyroscope
Bias Instability	20 ug	3 °/hr
Initial Bias	< 5 mg	< 0.2 °/s
Initial Scaling Error	< 0.06 %	< 0.04 %
Scale Factor Stability	< 0.06 %	< 0.05 %
Non-linearity	< 0.05 %	< 0.05 %
Cross-axis Alignment Error	< 0.05 °	< 0.05 °
Noise Density	150 ug/$\sqrt{Hz}$	0.005 °/s/$\sqrt{Hz}$

Accuracy of a sensor can be defined in several ways. The absolute limits of the error are one simple option. However, this is usable only if the error stays within reasonable limits through the full scale of the sensor. For example, if the scale goes from 0 to 100, an absolute error of 1 would be quite small near the values of 100, but significant if the measured value was near 0. It also requires that the error does not depend on the magnitude of the measured value. Instead of an absolute value, the error can be defined as a percentage of the measured value, or the full scale value. If the percentage is of the full scale value, then it is basically the same as absolute value. Given a full scale of 500 and error of 2% would mean the absolute error value of 10. Defining the error as a percentage of the measured value gives a dynamic range for the error. When the measured value changes, the error also changes. Beside these, the error can be defined based on the possible output values. Consider a digital output value consisting of one byte or 8 bits. This gives us 256 possible values. The error could be defined as 2. If the measured value produced a digital value of 150, then the real value would be inside the range of 148 to 152. Defining error based on the output values can be useful in sensors that have a digital output format allowing the error to be expressed, for example, in units of LSB [19].

3.3 Repeatability and reproducibility

Repeatability is described as the sensor's ability the produce same measurements when the measurand remains the same. Ideally, the result should be the same if the situation does not change, but due to imperfections in the measurement process this is not the case. Repeatability error is therefore caused by a sensor that is unable to produce the same values under similar conditions. Reproducibility is the same as repeatability but over a long period of time. For example, if a sensor produces the same values in a certain day during a short period, it has good repeatability. However, if the same measurements are repeated on the next day, but the values differ from the previous day, then the sensor has bad reproducibility. These concepts are illustrated in Figure 3.1. The figure represents the targets from a shooter from two separate days. Both days the shooter has good repeatability since the shots are very close to each other. However, since they are not close if we compare the shots from different days, the shooter has bad reproducibility [20].

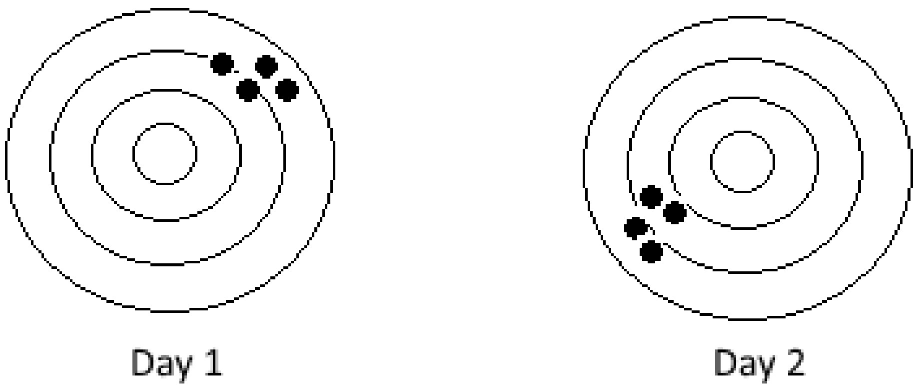

Figure 3.1 *Repeatability and reproducibility*

3.4 Nonlinearity

If the relation between input and output is expected to follow a linear function, but in reality does not, an error called *nonlinearity* is introduced into the measurement. The value of the nonlinearity error is the largest difference between the linear approximation and the real transfer function. Figure 3.2 illustrates this concept. L_0, L_1 and L_2 are alternative linear approximations. L_0 is drawn between the minimum and maximum output values or *terminal points* [19]. The error is smallest at the terminal points but higher elsewhere. L_1 and L_2 produce lower errors in the middle of the output range but higher errors at the extremities. Depending on the situation different linear approximations can provide better results than others.

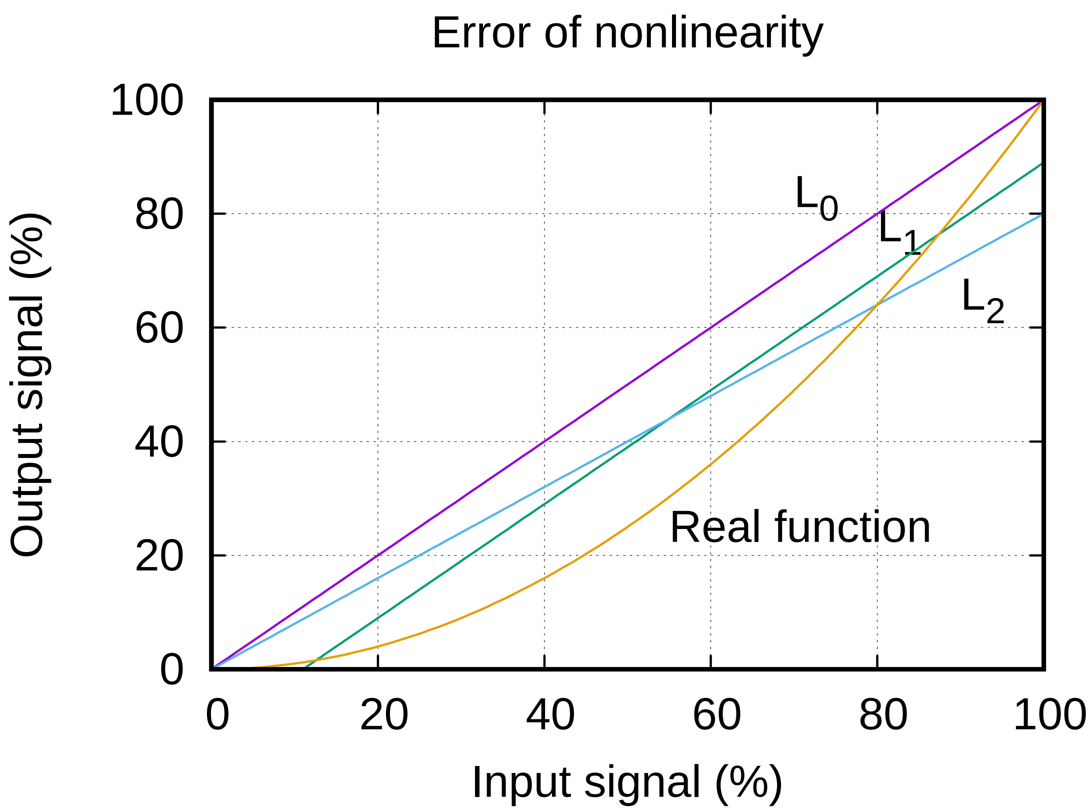

Figure 3.2 *Error of nonlinearity*

3.5 Resolution

Resolution is the smallest change in the measurand that a sensor is able to detect. Since sensor outputs are usually digital, they are divided into a fixed number of small intervals. Each interval will represent a range of real measurand values, where the output will be the same for all of them. Resolution can be expressed as an absolute value, a percentage of the full scale, or how many bits the output contains. For example, if the full scale range is one meter and the sensor has a 2-bit resolution, the scale would be divided into four parts each being 25 centimeters long.

3.6 Hysteresis

Some sensors suffer from a phenomenon called hysteresis. It occurs when a certain point is approached from two different directions. The output will not be the same even though the physical value is. Consider a situation where we are moving towards value x from values smaller than x. When we have reached x the sensor outputs value y_1. Now in a different situation we are moving towards x from values larger than x and once we reach x the sensor outputs value y_2. The difference between y_1 and y_2 is called hysteresis. It is caused by physical characteristics of the sensor. See Figure 3.3 for illustration of hysteresis.

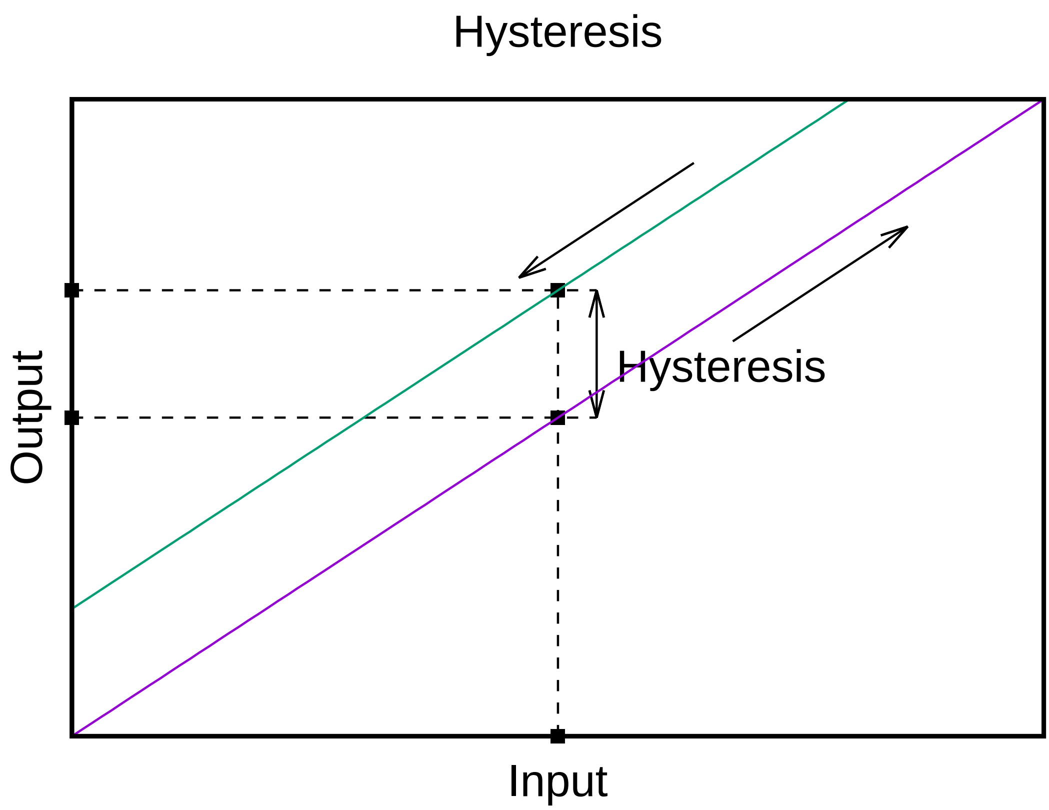

Figure 3.3 *Hysteresis*

3.7 Saturation and dead band

A dead band is a range inside the scale of the sensor where it does not respond to any change in the measurand i.e. the sensor is basically dead inside that range. In that range the output of the sensor will stay near some value, usually zero, over the entire range which is called a dead band. Figure 3.4 shows the output function of a sensor with a dead band near zero.

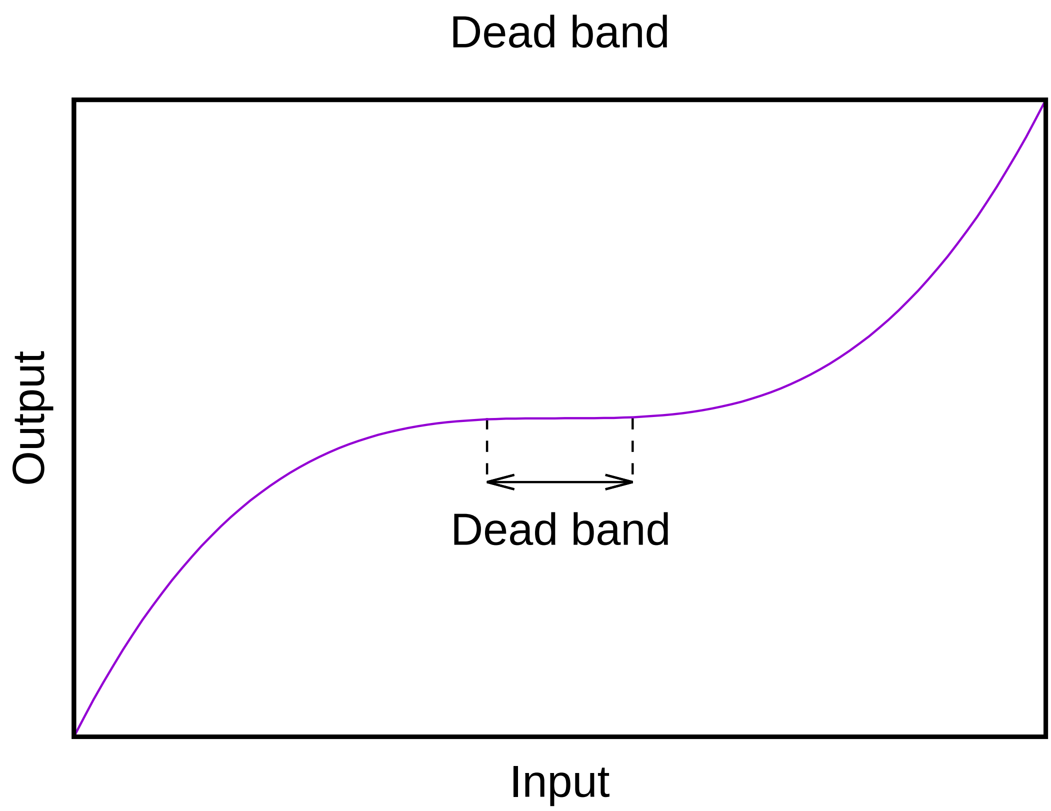

Figure 3.4 *Dead band*

Saturation happens when a sensor is pushed over its operating limits. After a certain point, the sensor stops responding to input and is unable to produce reasonable measurements. Figure 3.5 illustrates saturation.

3.8 Bias and bias instability

Bias is an average offset in the measurement from the actual value of the measurand. For example, bias is the value a gyroscope is outputting when it is not experiencing any rotation. Bias has no correlation with the measurand. For accelerometers, it is typically given as m s$^-$2 or for gyroscopes as $^\circ$/h.

Bias instability defines a random variation in the actual bias i.e. how much or fast does the bias change over time? It is expressed in the same unit as bias. Larger instability will make it harder to track and compensate for, increasing the inaccuracy of the sensor [26].

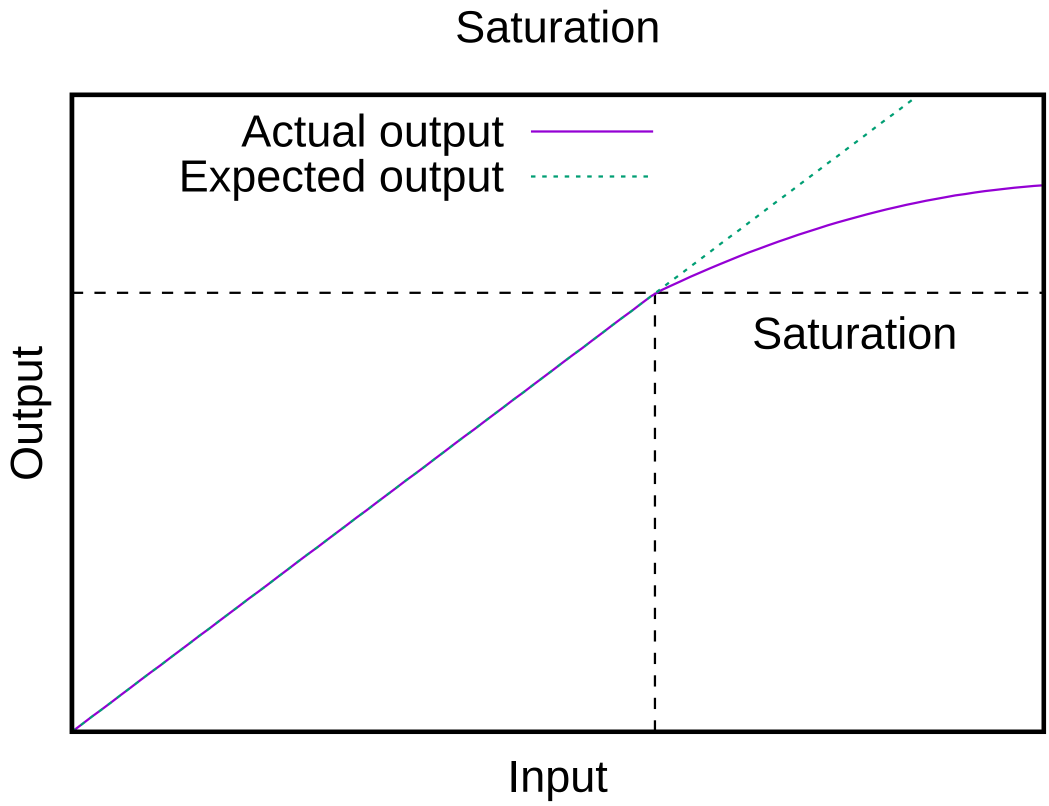

Figure 3.5 *Saturation*

3.9 Random walk

A random walk is an accumulated error caused by random noise. Gyroscopes and accelerometers have two different random walks. Random walk for a gyroscope divides into the angle random walk and the rate random walk. The angle random walk is usually given as $^\circ/\sqrt{h}$ and is caused by *uncorrelated noise* in the angular rate. The rate random walk is usually given as $(^\circ/\mathrm{h})/\sqrt{h}$ and is caused by noise in the angular acceleration.

The random walk for an accelerometer divides into the velocity random walk and the acceleration random walk. The velocity random walk is usually given as $(\mathrm{m/s})/\sqrt{h}$ and is caused by noise in the acceleration. The acceleration random walk is usually given as $(m/s^2)/\sqrt{h}$ and is caused by noise in the jerk [26].

4. SENSOR TYPES

A vehicle navigation system usually utilizes several different sensors. Use of multiple sensors allows better accuracy and mitigation of sensor errors. It can also allow navigation even if one or more sensors fail completely, for example, due to a mechanical failure. We can divide the different sensors into two categories based on what kind of measurement they provide. This chapter defines relative and absolute sensors, compares them, and provides examples of sensors from both categories often used in navigation systems.

4.1 Relative measurement sensors

A relative measurement sensor provides measurements that are with respect to the body of the vehicle, and not to earth, or any other known fixed frame. It can measure a change in the position, velocity, or attitude from the previous position. If the initial position is not known, a relative sensor has no way of determining the absolute position of the vehicle. Even if the initial position was known, a relative sensor is not sufficient, since error accumulation would eventually cause the navigation result to drift away from the correct one. Because of this, a proper navigation system can not consist only of relative sensors. Purpose of a relative measurement sensor is often to provide the navigation result between absolute measurements that can not provide real-time navigation such as a marker detection sensor discussed in subsection 4.2.2. Relative sensors, such as encoders and inertial sensors provide frequent updates, making it possible to know the vehicle position at a high rate.

4.1.1 Gyroscopes

A *gyroscope* is a device that measures the rate of turning. In a vehicle moving on a flat surface, a gyroscope is used to determine how fast the vehicle is currently turning. First gyros were implemented using spinning-mass technology. Currently, gyroscopes

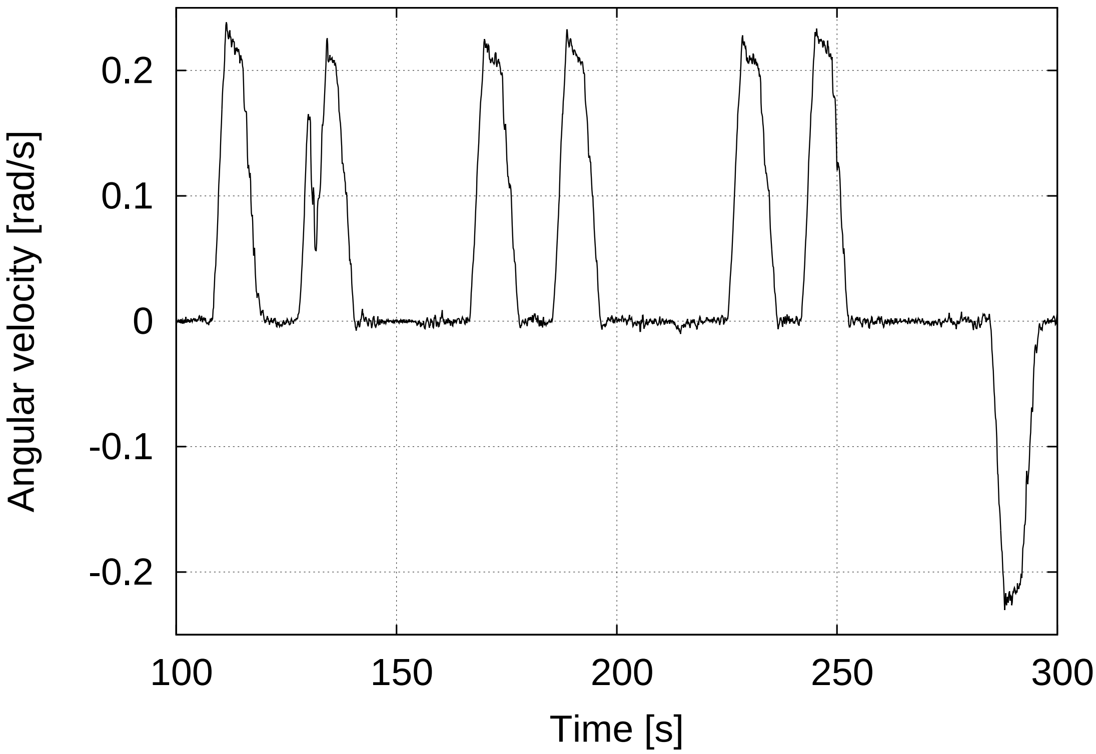

Figure 4.1 *MEMS gyro angular rate in a moving vehicle.*

used in navigation systems are most likely vibratory or optical [24]. Accuracy of a gyroscope can vary greatly depending on the model. For an accurate gyro, the bias can be small as 0.0001 °/h but even as high as 1 °/s [38]. Even if we are navigating on a flat surface, a gyroscope may be needed to obtain the attitude of the vehicle. Consider a situation where the vehicle has a GNSS receiver with an antenna placed at the top of the vehicle. If the height of the vehicle is large, and the vehicle experiences tilting, it will move the antenna from the expected position and result in larger errors with GNSS positioning. Getting the attitude from the gyroscope allows us to compensate the tilt of the vehicle, and achieve a better accuracy. A vehicle with the height of 10 meters and roll angle of 1 degree would result in 17 centimeter lateral error in GNSS position, if not compensated. It is not uncommon for a vehicle to experience large roll and pitch angles during cornering, braking, and accelerating. Figure 4.1 shows an example of MEMS gyroscope yaw rate from a moving vehicle. The vehicle was driven in straight lines with 90 degree turns.

Spinning-mass gyroscope was invented in 1852 by Jean Bernard Léon Foucault [36].

It utilizes a physical object that is spinning, and the principle of conservation of angular momentum. The mass is suspended inside a case where it is allowed to rotate freely around both of the axes perpendicular to the spin axis of the mass. If the case is now rotated, the spinning mass will remain aligned respect to the inertial space. We can now measure the angle of the mass with respect to the case to determine how the sensor has rotated.

A vibratory gyroscope works on the basis of detecting the Coriolis acceleration of a vibrating element. The element can be, for example, a string. When the gyro is rotated, the vibratory element vibrates due to the Coriolis effect. Measuring the amplitude of the vibration gives us the angular rate. Figure 4.2 illustrates the working principle of a vibratory gyroscope. MEMS technology is often used in vibratory gyros providing low-cost sensors [27].

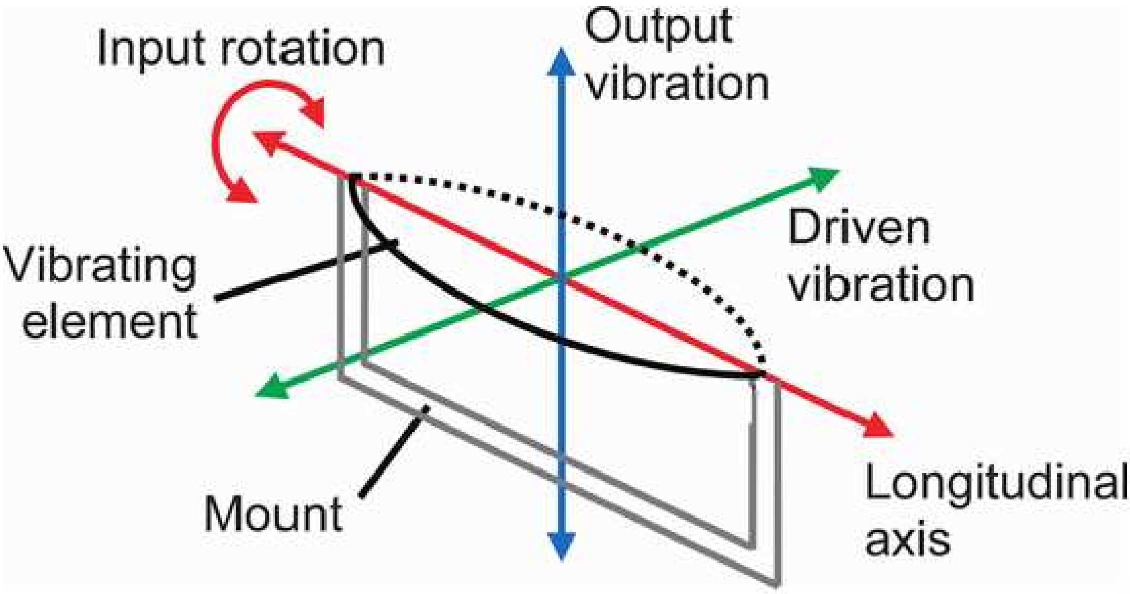

Figure 4.2 *Vibratory gyroscope [23, Figure 4.10]*

Optical gyroscopes are based on the fact that light travels with a constant velocity. The gyro consists of a structure that guides light waves, called a waveguide, such as fiber optic or mirrors. If two light waves are sent in the opposite directions to a closed-loop waveguide, they will travel the same distance if the loop is not rotated. Now, if the loop is rotating the distance travelled for the light travelling in the same direction as the rotation will increase as the reflecting material is moving away from the light. Light travelling in the opposite direction of the rotation will result in smaller distance as the reflection material is moving towards the light. Figure 4.3

illustrates this. Changes in path lengths can be measured and used to determine the angular rate of the gyroscope.

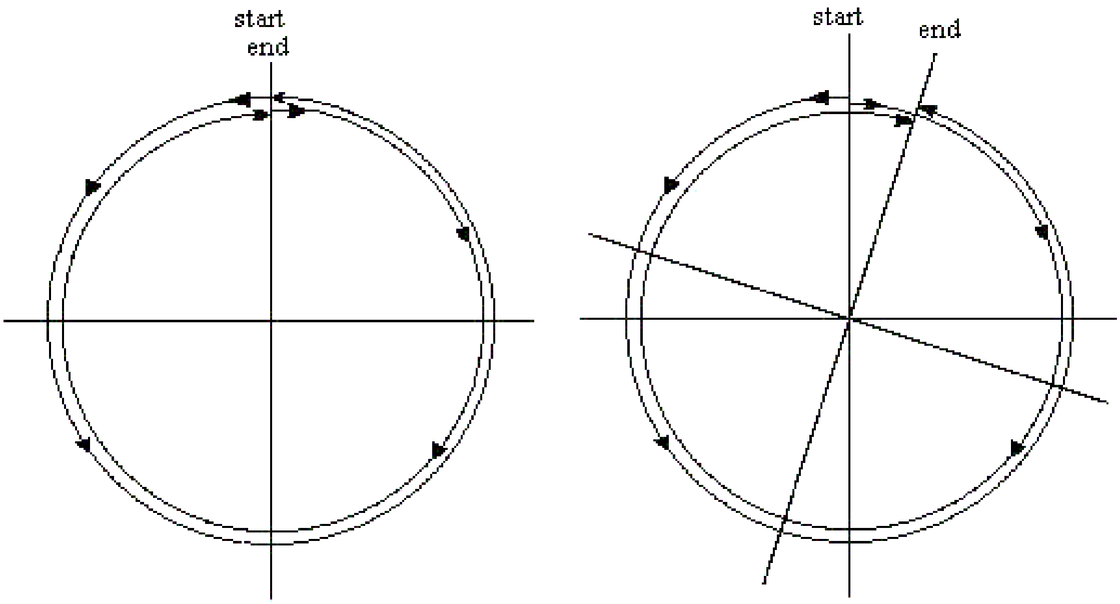

Figure 4.3 *Optical gyroscope [13, Chapter 2.7]*

Besides these technologies, a few others also exist. Cold-atom interferometry can offer much better accuracy than the traditional gyros. Nuclear magnetic resonance offers high performance on a small scale. Accelerometers could also be used to measure the angular rate [17, 37, 18].

4.1.2 Accelerometers

Accelerometer measures acceleration inflicted on a given sensitive axis. A simple accelerometer consists of a mass suspended by springs. When an acceleration is inflicted on the sensor, the mass moves along the axis that it is measuring. By measuring the displacement of the mass along the axis, we can obtain the acceleration of the sensor. For a vehicle navigation system, an accelerometer provides information about how the vehicle is moving. Accelerometers currently used in vehicle navigation systems are based most likely on pendulous or vibrating-beam models (VBA) [23]. Figure 4.4 shows example acceleration data in a moving vehicle. The figure contains only one axis that is in the longitudinal direction.

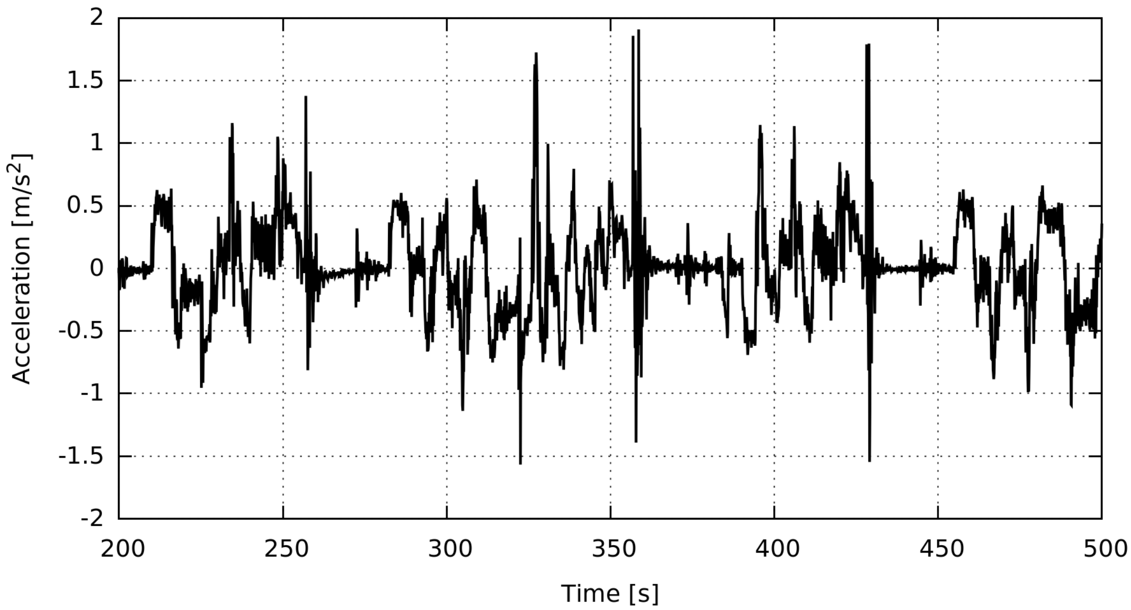

Figure 4.4 *Levelled accelerometer measurements*

4.1.3 Inertial measurement units

An inertial measurement unit (IMU) is a device that consists of three gyroscopes and three accelerometers each measuring one axis, providing a fully working 3-dimensional measurement system. Gyroscopes and accelerometers are usually bundled together as a single IMU, and not as individual sensors. IMU measures the force and angular rate in all three axes and is capable of providing an independent navigation solution. Accuracy of such system is naturally dependent on the model of the IMU. Figure 4.5 gives a simplified example of the main elements in an inertial measurement unit. A temperature sensor is used to compensate for errors that change with the temperature.

4.1.4 Wheel encoders

Wheel encoder, or an odometer, is a sensor for measuring travelled distance by a vehicle with wheels [16]. It measures the rotation of the wheel. Odometer readings can be used to calculate the yaw rate and velocity of the vehicle. Solving the yaw rate of the vehicle is done by measuring odometry from both sides of the vehicle and then comparing the difference. This method is called differential odometry. Differential

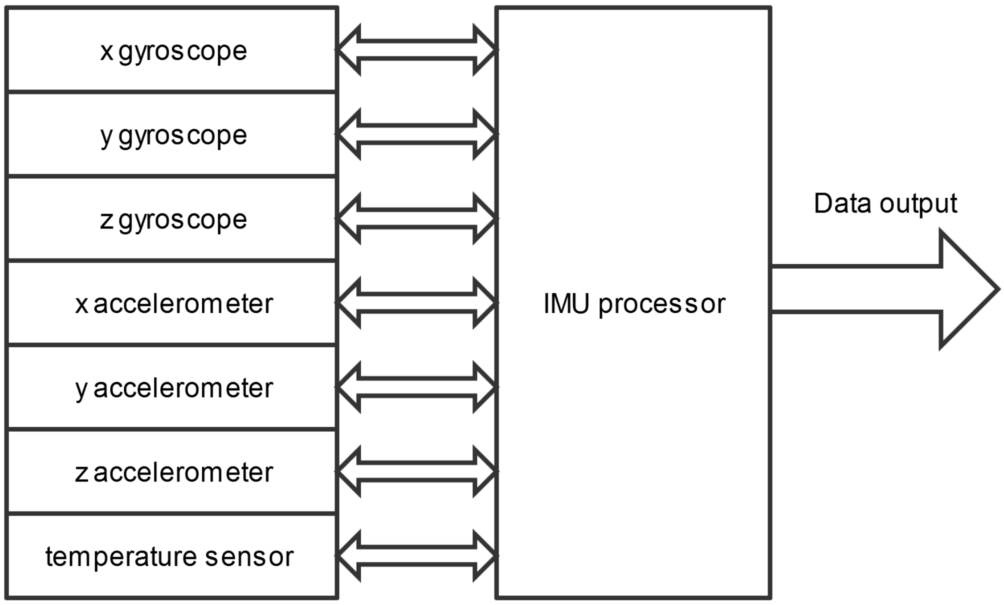

Figure 4.5 *Simplified schematic of an inertial measurement unit*

odometry requires minimum of two sensors on the opposite sides of the vehicle. The largest source of the error in odometers comes from an inaccurate wheel radius. Even a small error in the radius will result in a large error in the navigation result. Vehicle moving at a velocity of 10 m $s^{-}1$ and a wheel radius error of one percent would result in odometry error of 0.1 m $s^{-}1$. An error this large is quite significant, and shows the importance of finding the correct wheel radius value. Multiple sources can affect the wheel radius. Up to one percent of error can be caused by tyre pressure, the temperature, the vertical load of the wheel, and velocity [21]. During operation, the tyre also wears down and the radius decreases. Because of these effects, for an accurate navigation systems using odometry, it is recommended to use other sensors to estimate the wheel radius during operation. This can be achieved, for example, by using a marker detection sensor described in subsection 4.2.2. Other sources of error include *wheel slip* and *quantization errors*. Quantization errors are only short-term and will be corrected with future measurements [14].

An encoder produces a pulse signal proportional to distance travelled. Counting the number of pulses or ticks combined with the wheel radius, and a known scale factor, we can calculate the distance travelled by the wheel. Odometers used in navigation systems are often Hall effect, or optical sensors, which provide high accuracy even at

Figure 4.6 *Optical encoder [30].*

small velocities [23]. A Hall effect sensor consists of a toothed wheel, which produces a pulse every time one tooth passes the sensing element. Optical sensor uses a light source and a light sensing element. As the wheel rotates it will block the light and let it go through in turns resulting in a pulse signal. Figure 4.6 illustrates an optical wheel encoder. One on the left is an incremental encoder that counts total pulses and the one on the right is an absolute encoder that reports the absolute position of the encoder.

4.1.5 Steering encoders

If a wheel of the vehicle is able to steer, a wheel encoder will not be sufficient to produce enough measurements for working odometry. Consider a situation where two wheels are rotating the same amount and steered to a certain angle. If the only sensors available are wheel encoders, it is impossible to determine if the vehicle is going straight, or if the wheels have been turned, and it is driving to the left or right. We could only determine to distance travelled, but not the direction. Steering encoder outputs the absolute angle of the wheel with respect to an agreed frame. Usually an angle of zero degrees means that the wheel is aligned with the vehicle frame i.e. it is pointing forward. Errors in steering encoders usually arise from misaligned wheels and improper calibration i.e. the sensor has a constant bias.

4.2 Absolute position measurement sensors

Absolute position measurement sensors are a vital part of any vehicle navigation system. They provide measurements respect to the Earth, or to another fixed coordinate frame. Without absolute measurements, the navigation position would eventually drift from the actual position because of sensor errors. Also, if the initial position is not known relative sensors alone could never find the actual position no matter how accurate the sensors are. Therefore, a vehicle navigation system needs to have at least one absolute measurement sensor. The most common absolute sensor is a satellite navigation receiver. Other sensors include local marker detection sensors, such as radars, lasers, inductive wires, cameras, and pseudo satellites [22, 29]. The next two chapters will take a closer look into satellite navigation receivers and marker detection sensors.

4.2.1 Satellite navigation receivers

A satellite navigation receiver is a device that utilizes Earth-orbiting satellites to obtain a three-dimensional position of the sensor with respect to the satellites. Each satellite is part of a system, and a receiver can utilize one or multiple systems at the same time. A satellite navigation system can have a global range, and such a system is called a global navigation satellite system (GNSS). Otherwise it is a regional system. A regional system only covers a certain limited area. Using multiple

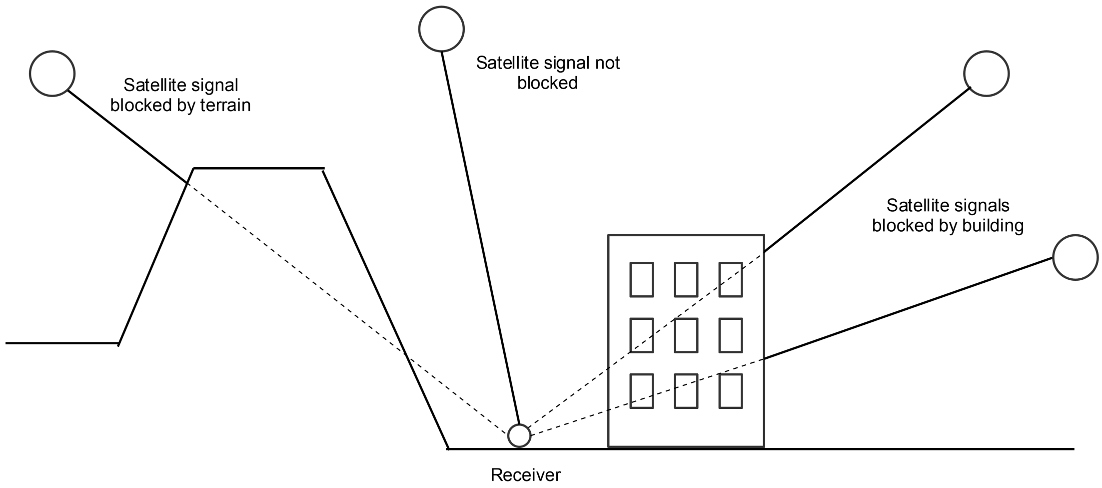

Figure 4.7 *Satellite navigation signals being blocked*

systems can allow better accuracy than one could provide. Compared with other sensors, satellite navigation is quite easy to implement, since the complex calculations are already implemented inside the receiver, and it can offer absolute position measurements in a global range. However, it is not enough for a fully working reliable navigation system in many situations. Signals get blocked easily by terrain, buildings, and other structures [15]. Going in to a tunnel or a cave would also completely block satellite navigation. Figure 4.7 shows how easily the signals can get blocked even if multiple satellites are above the horizon of the receiver. Accuracy of a standard GNSS is usually in the range of a few meters. However, this can be improved using differential GNSS (DGNSS) or real-time kinematic (RTK).

A *differential* global navigation satellite system is an improvement over existing GNSS to provide better accuracy. In the best cases, it provides accuracy under one meter. DGNSS works by using fixed ground stations, known as reference stations or base stations, that broadcast correction signals. These stations measure pseudo ranges to actual satellites and calculate differences between known pseudo ranges. These differences are then broadcast to all receivers within range. Devices capable of DGNSS can utilize the corrections to correct their own pseudo ranges to specific satellites and obtain better accuracy. Accuracy of the corrections is dependent on the distance between the base station and the receiver. Accuracy decreases about 1 cm for every 1 km [25]. Figure 4.8 illustrates the basic idea behind DGNSS.

Real-time kinematic (RTK) works by utilizing corrections sent by a base station as

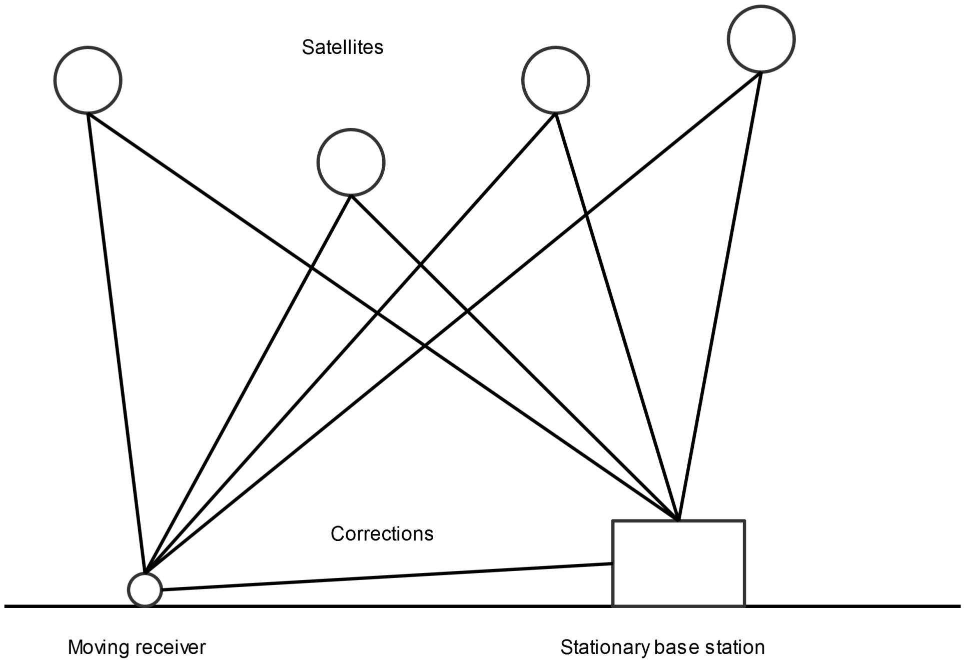

Figure 4.8 *Differential global navigation satellite system*

DGNSS, but the technique differs from it. RTK provides accuracy to centimeters in optimal conditions. It works by measuring the phase of the radio frequency carrier signal, whereas DGNSS uses the baseband signal. RTK requires one base station, and it is usually confined to a certain location. It is also referred to as *carrier-phase positioning technique.* RTK base station sends the phase of the carrier wave to moving receivers, which then compare it with their measurements of the phase. The need for a base station and its limited range limits the usefulness of RTK in a vehicle navigation system where the vehicles are not confined to a certain area. However, for systems requiring excellent accuracy from a GNSS, RTK provides that [23, 25].

The Global positioning system (GPS), also known as Navstar, is maintained by the U.S. Air Force. Currently, it consists of 31 satellites. The first satellite was launched in 1978 [2, 33]. The GPS provides two different services based on the user. Standard positioning service (SPS) and precise positioning service (PPS). SPS is intended for civilian use and is available for all users. PPS is only available for users authorized by the U.S. government. These include, for example, U.S. military and NATO forces. PPS signals are encrypted to prevent unauthorized use. U.S. government has the ability to severely decrease the accuracy of the SPS, if they deem it necessary, and have done so in the past using *selective availability* (SA) [11]. This means that any navigation system that relies on accurate GPS can be taken out of service by the U.S. government at any time. GPS is the only satellite navigation system that has SA functionality [12]. However, new GPS satellites do not have SA functionality in them so as older models get replaced it will eventually cease to exist [6].

Global'naya Navigatsionnaya Sputnikovaya Sistema (GLONASS) is quite similar to GPS, with the main difference that it is owned and maintained by Russia. It currently consists of 24 satellites, first launched in 1982 by the Soviet Union. Like GPS, it also provides two different services. One service is limited to military use only, and the other is for civilian use. Accuracy of the GLONASS is very close to GPS, but both are currently designing, developing, and launching new generation satellites that will increase the accuracies of the systems [23, 4].

Galileo is the first civilian satellite navigation system [23]. It is owned and maintained by the European Union. The first test satellite was launched in 2005, and first operational one in 2011. Currently, Galileo consists of 14 satellites, and it is scheduled to achieve full operational capability (FOC) in 2020. When finished, Galileo is expected to have similar or even better accuracy as GPS [3].

Beidou and Compass are Chinese systems. Beidou-1 provides satellite navigation only in China using three satellites. Beidou-2, or Compass, has a global range and consists of 21 satellites. The first satellite was launched in 2000. Like GPS and GLONASS, Beidou also has two levels of service. One for military and one for civilian use [8].

Indian Regional Navigation Satellite System (IRNSS) is a regional satellite navigation system. The purpose of IRNSS is the provide navigation in India, if other systems are not able to. It currently has 7 satellites and the first was launched in 2013. It also includes separate military and civilian services. [10].

Quasi-Zenith Satellite System (QZSS) is a regional satellite navigation system to provide augmentation for GPS in Japan. Currently, it has only one satellite launched in 2010. Once finished, it will have four satellites. Full operational capability is expected to be reached in 2018. QZSS is intended for civilian use only [9].

4.2.2 Marker detection sensors

Marker detection sensor works by detecting markers placed in the area where the vehicle is driving. It produces absolute measurements in the local coordinate frame, where each marker has a fixed position. When a marker is detected, we can compare the current vehicle position and known marker position in order to determine the correct position for the vehicle. Markers can be divided into two types. One group is unique markers where each marker is unique and every detection can be unambiguously mapped to a marker at a fixed position e.g. radio transponders. Second group consist of markers that are not unique. In this case detections can not be mapped to a unique marker, but to several similar ones. Such cases require previous measurements to be taken into account when mapping detection to a marker. In some cases, it will be impossible to make a decision about what marker the detection represented. Magnets and radar reflectors are an example of such markers that can not be unambiguously mapped. Marker detection allows very accurate navigation, even down to millimeters in optimal situations, making it an ideal solution for AGVs that require high accuracy. However, while it provides excellent accuracy and reliability, it is limited to the area where the markers are installed. Installation and surveying of the markers can also be expensive and difficult.

Magnet detection sensor works by detecting magnets installed near the vehicle path, e.g. into the ground. It will provide detections of magnets relative to a sensor installed in the vehicle. The sensor produces detection, which is then mapped to a single magnet based on the current position of the vehicle. The detection will map to multiple magnets but utilising the current position of the vehicle, and the previous detections we should be able to make a confident decision, and decide on a single magnet. A magnet sensor is reliable since it does not require any contact, and is not influenced by weather conditions. It can work in the rain and snow making it a very robust navigation sensor. One of the main problems in magnet sensors is the short sensing distance. Strength of the magnetic field decreases drastically as the distance becomes larger, making it more and more difficult to detect magnets. The sensor can not be placed too low because then we would introduce the risk of it being physically damaged by an external object in the ground or an uneven surface. A magnet sensor can produce different kinds of errors. A magnet that is within the range of the sensor, but the sensor does not detect it, is called a *missed magnet*. Multiple missed magnets can severely affect the navigation result. A magnet can be otherwise detected correctly, but the polarity of it can be incorrect i.e. the south and north pole get mixed. A sensor can also report detection even if no magnet was actually present, causing a *false detection*. While a magnet navigation sensor can produce high accuracy, it is affected greatly by the accuracy of the odometry. If the odometry is not accurate enough, mapping the detections to correct magnets will be difficult, and navigation based on magnets might not even be possible.

A Hall effect sensor measures changes in the magnetic field. The Hall effect, discovered by Edwin Hall, produces voltage in a conductor if a magnetic field is inflicted on it. A Hall effect sensor measures changes in the voltage, and determines the direction and density of the magnetic field based on the sign and magnitude of the voltage [34].

A Fluxgate magnetometer is an alternative technology for magnetic sensors used in vehicle navigation systems. It consists of two coils, and a core that is magnetically sensitive. One of the coils is induced to alternating current that will cause the core to go through a saturation cycle i.e. changing between magnetized and unmagnetized. The changing magnetic field will cause current in the second coil which is measured. If the input and output currents are the same, the measured magnetic field will be neutral. Exposing the core to a magnetic field will change the output current to larger or smaller depending on the field. Difference between input and output current will indicate the direction and density of the magnetic field [28].

5. TESTING PLATFORMS

Different platforms were used in testing and verification during the project. Each platform had its strengths and weaknesses. Simulation was cheap and fast but required software development at the start, and did not represent the physical world entirely. A small testing vehicle allowed indoor testing with real sensors. However, due to different geometry, it could not fully replace the full size vehicle. Using the small testing vehicle was also somewhat slower in comparison to simulation. The full scale vehicle was the only complete testing platform, but it required a large testing field and the vehicle itself, making testing on it quite expensive. All of the three platforms served a specific function during the project, and were used extensively. Naturally, at the start of the project, focus was more on the simulation, which then moved to the indoor testing vehicle, and finally ending in the full size vehicle. At the later stages of the project, testing focused on the simulator and full size vehicle.

5.1 Software simulation

This project was started by making a standalone software simulation to be used for testing the navigation software. It quickly proved to be an excellent platform, allowing fast and continuous testing and development. The simulation allowed the programmers to make changes in the navigation and test them immediately. Compared with the alternative, where the development would have been done with a physical vehicle, simulation was clearly a better choice, at least in the early stages of development. Not having a simulator would have increased total project time significantly even after taking the development time of the simulator into account. Therefore, software simulation was the primary and the most used testing platform during the project. It has an additional major benefit over the physical vehicles, as it is possible for each developer to run their own simulation at the same time, allowing multiple persons to develop and test simultaneously.

The simulation software consists of a graphical user interface (GUI) and a simulation of the world. The GUI allowed the user to control the simulation i.e. move the vehicle and see what was happening. The input given by the user was fed to the actual simulation, which was transformed to the movement of the vehicle and finally the movement was used to produce measurement data that the real navigation sensors would have produced in a similar situation. Figure 5.1 illustrates the basic architecture of the simulation.

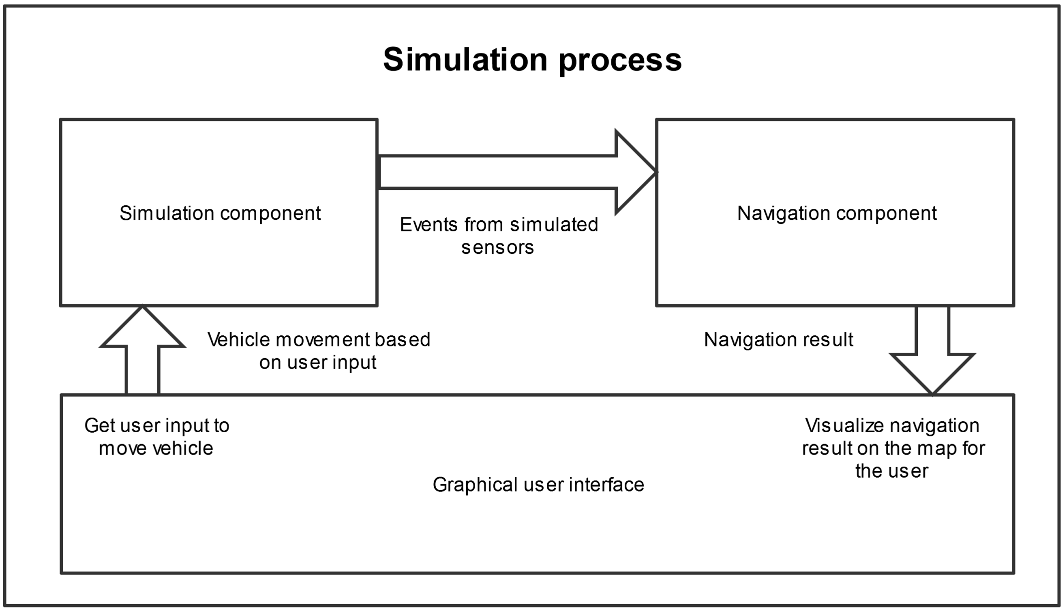

Figure 5.1 *Simulation architecture*

Software events were used as the communication method between the simulation and navigation in the basic simulation mode. Later in the project, the simulation was enhanced with the capability of sending real messages in a physical *controller area network* (CAN). This allowed for a sophisticated simulation closer to the real physical vehicle and sensors. Figure 5.2 shows the graphical user interface of the simulation software implemented and used during the project.

The simulation used a flat horizontal plane as the world with the purpose of generating stimulus for the navigation sensors. A two-dimensional simulation was chosen, because it was faster to implement, and adding a third dimension was deemed unnecessary. However, this meant that, for example, the tilting of the vehicle could not be simulated. Simulated sensors included a GNSS receiver, accelerometers, gyroscopes, wheel encoders, steering encoders, and marker detection sensors. The simulator sup-

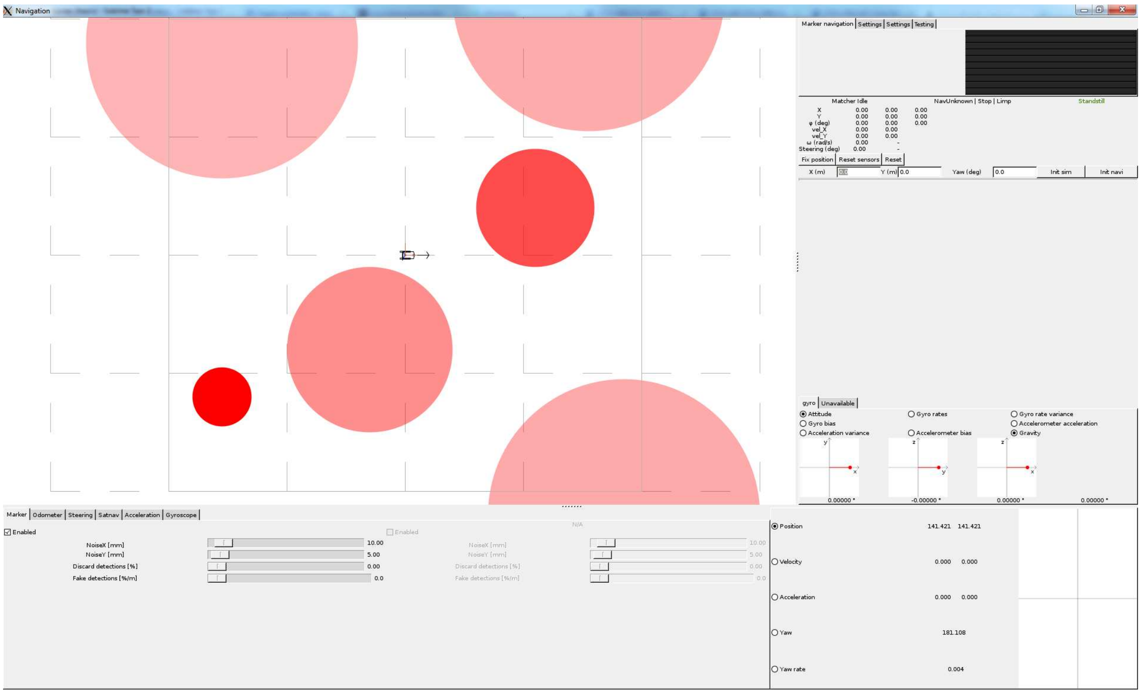

Figure 5.2 *Simulation software GUI*

ports an unlimited number of any sensors in any position of the vehicle. Since the simulated world and the sensors are ideal and free of errors, user-defined arbitrary errors could be added to the simulated measurements. The errors included bias, bias instability, scaling error, random noise, random walk, and false measurements depending on the sensor type. The simulator used a discrete-time simulation to simulate the movement of the vehicle and sensor outputs. Simulation was run one step at a time with a time difference typically in the range of 20 to 100 ms between each step. A shorter step produces more accurate simulation but requires extra processing time from the computer.

Besides the simulation, the software functions also as a graphical user interface only. It can be connected with a live navigation software through an Ethernet connection and used to visualize what is happening in the navigation system. This is illustrated in Figure 5.3.

5.2 Replaying real data

Replaying real sensor data gathered from a physical vehicle was an extension of the software simulation. It allowed making modifications to the navigation and

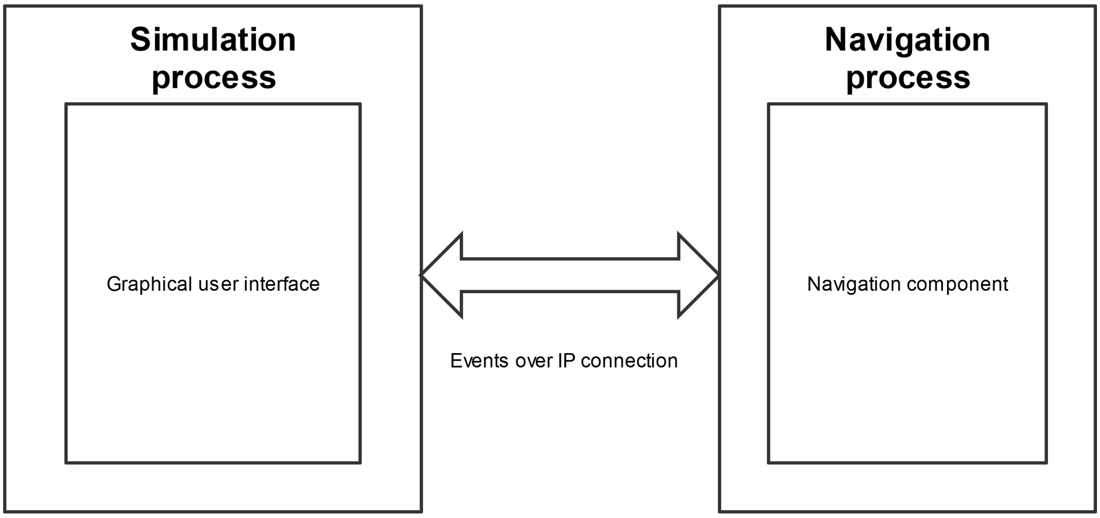

Figure 5.3 *Navigation visualisation*

examining the effects on the same input. The simulation component itself was replaced with a data reading component, which reads data written to a log file and converts it to messages from the sensors, which are then fed to the navigation component. Figure 5.4 shows the architecture of the data replay platform.

The data gathered from the sensors during a test run was saved into text files. When replaying data, these files were given as input to the log reading component, which then fed the messages it read from the files to the navigation software. Navigation software would then execute the navigation algorithms again and output the navigation result.

5.3 Physical vehicles

Developing a perfect simulator that would fully imitate the actual physical vehicle is impossible. No matter how well the simulator is implemented, it will never be the same as the actual vehicle. When making a software simulation, it is often a compromise between the time and the quality of the simulator. Therefore, a physical testing vehicle is needed in order to properly test and verify the correctness of a vehicle navigation system. A physical vehicle comes with an unknown number of features that are difficult to simulate correctly. Sensor errors, wheel slipping, inertia, friction, and tilting of the vehicle are just a few examples.

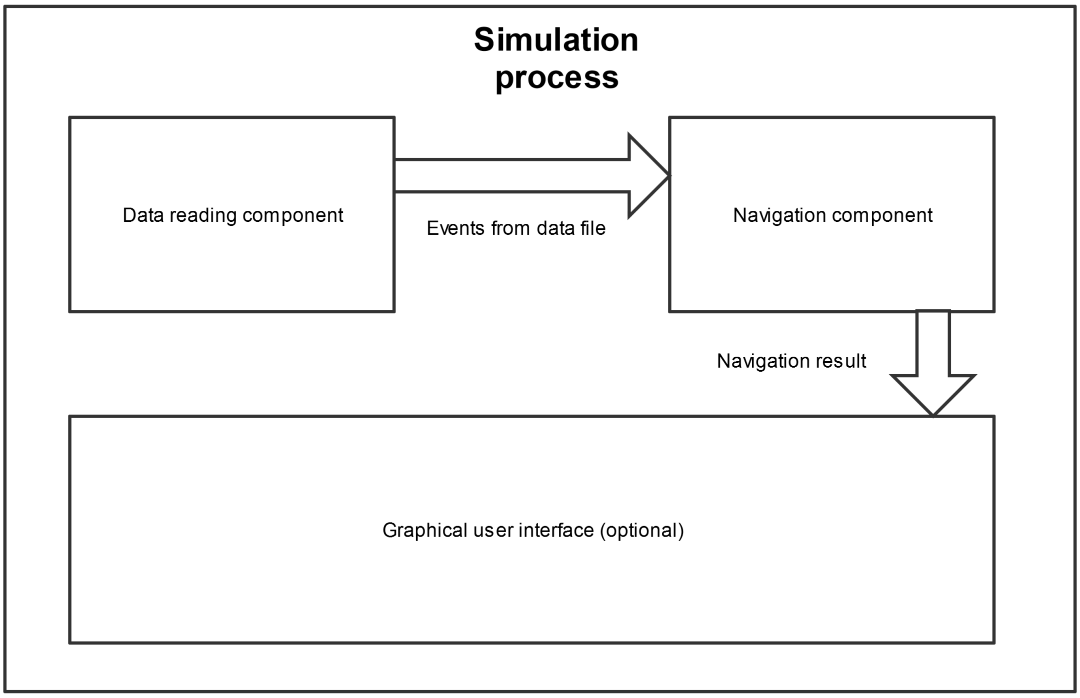

Figure 5.4 *Data replay architecture*

We can divide physical vehicles into two groups. The first group consists of smaller vehicles that try to resemble the actual vehicle as much as possible, while remaining small and inexpensive. An example of a smaller testing vehicle used in this project is given in subsection 5.3.1. Second group is the actual vehicles for which the navigation system is ultimately intended. A full scale or full size vehicle used during the project is discussed in subsection 5.3.2.

5.3.1 A smaller testing vehicle

For this project, a smaller test vehicle, capable of indoor testing was built. The vehicle itself was a modified wheelchair with integrated wheel encoders in the rear wheels. It did not include any other sensors by default, so they were installed during the project. The wheelchair proved to be quite useful. It was small enough to be driven inside but had plenty of room for installing several sensors. However, it was quite large and heavy, about 100 kilograms. This limited the testing maneuvers as driving the vehicle indoors had to be done carefully and required two people if the vehicle had to be lifted. A slightly smaller testing vehicle most likely would have been a better alternative. Also, the ability to remote control the vehicle would have been useful, but since the wheelchair could be driven while sitting in it, the lack of remote control was not a large deficiency.

As mentioned earlier, the vehicle had two wheel encoders pre-installed but no other sensors. During the project, an on-board computer and multiple sensors were installed in the vehicle. The on-board computer was an industrial grade Linux computer. A wireless local area network (WLAN) was used to communicate with the on-board computer. The sensors included an inertial measurement unit, a satellite navigation receiver, and two marker detection sensors. Satellite navigation testing was conducted outdoors since the satellite signals could not be received indoors. Figure 5.5 shows the wheelchair used in office testing with all of the sensors installed. The inertial measurement unit and satellite navigation receiver are hidden inside the vehicle and not seen in the image.

During the project, the wheelchair was used as a primary testing platform for sensor and driver software testing, and as a secondary platform for navigation testing. Device and driver testing in the full scale vehicle would have increased the costs of testing and taken more time. In addition, device and driver testing in the full size vehicle would have been dangerous. For example, it is quite easy to interpret sensor readings in the wrong direction. This could lead to a situation were the navigation, and therefore the vehicle, are moving in the opposite direction from expected. A situation of this kind is potentially very dangerous and can cause extensive damage. The testing vehicle in the office with real sensors allowed the rapid testing and verification of the software, and reduced development costs. The vehicle was driven manually by a joystick attached to the vehicle, either by walking along the vehicle, or sitting inside the vehicle.

Although it was an excellent testing platform, the wheelchair had some shortcomings. The sensors installed in it did not represent the same sensors as in the full scale vehicle. Steering sensors were not installed and it had only two wheel encoders. The geometry of the vehicle did not match the full scale vehicle. The wheelchair had freely rotating front wheels and static rear wheels. In addition, the marker detection sensors were closely spaced, meaning they would mostly detect the same markers, whereas in the full scale vehicle the sensors were on opposite sides, detecting different markers. In an ideal situation, the testing vehicle would be the same as the full scale vehicle but in a smaller scale. In this way, the testing and verification

Figure 5.5 *Wheelchair testing vehicle*

needs with the full scale vehicle would be reduced even more.

5.3.2 A full scale vehicle

The third and final platform used in testing was a full scale vehicle. The vehicle was big and heavy and required a large outdoor testing field to be driven. Testing with it required a specific person who could operate the vehicle. This limited the availability of testing opportunities, and made it significantly more expensive than the other platforms. Weather conditions prohibited using the vehicle occasionally. For example, excessive snow or ice in the field made driving impossible. Maintenance was also required for the vehicle, sometimes preventing testing.

The full size vehicle had a total of 14 navigation sensors. The sensors included four wheel encoders, six steering encoders, one inertial measurement unit, two marker detection sensors, and a satellite navigation receiver. The vehicle was driven both in the manual and in autonomous mode. Manual driving was either done from inside the vehicle, or by using remote control. In autonomous mode, the vehicle was given drive commands by an external software and the vehicle was driven by an on-board vehicle control system.

6. TESTING METHODS

A vehicle navigation system is a complex system consisting of several parts and communicating with multiple hardware sensors, and most likely with external programs. For an autonomous vehicle, navigation is a vital part of it, and without knowing the position reliably, it can not operate. Therefore, it is important to ensure that the navigation system is reliable, and can function accurately in the required environments. In order to ensure this, suitable methods have to be established that can be used to verify the navigation system.

The testing methods used in this project ranged from straightforward ones, such as straight line driving, to more complex methods, such as absolute measurement tracking. Because the goal of the project was to replace an existing navigation system, comparing the new system with the old one was also used. This chapter takes a look into some of the methods used.

6.1 Straight line driving

Straight line driving was used as the first testing method when starting the verification process. It had three basic functions: initial navigation sanity check, wheel encoder calibration, and steering encoder calibration. Sanity check consists of verifying that every sensor was working as expected, and when the vehicle was moved navigation moved also in the same direction. This was used to eliminate any trivial errors, such as having interpreted wheel encoder readings inversely, or some other errors. Wheel encoder calibration is used to calibrate the wheel diameters. This is possible since we know the distance that was being driven, and can use that in order the calibrate the correct wheel diameters. Steering calibration, or verification, was to ensure that each steering encoder reports the same reading, which should naturally be zero, since the vehicle is driving in a straight line. Any offset from zero would add error to the odometry, and the navigation would wander from the expected straight line.

Table 6.1 shows wheel encoder calibration data using straight line driving as the calibration method. Testing was conducted with a full size vehicle by driving 105 meters in a straight line, first forward and then backwards. The distance was chosen as 105 meters, because it was the longest distance that could be driven in the testing field. Even though all the wheels are of the same make and model, and have the same nominal diameter, the calibration introduced notable differences in the diameters between the wheels. Equations used in the calibration procedure are shown in 6.1, 6.2 and 6.3.

Table 6.1 *Wheel encoder calibration*

Sensor position	**Front left**	**Rear left**	**Front right**	**Rear right**
Nominal wheel diameter [m]	1.8	1.8	1.8	1.8
Nominal ticks per revolution	10000	10000	10000	10000
Nominal ticks per meter	1768.388257	1768.388257	1768.388257	1768.388257
Ticks forward 105m	185538	179240	186219	178915
Ticks backwards 105m	185614	180114	186464	180046
Calibration				
Wheel diameter forward	1.801385	1.864681	1.794797	1.868068
Wheel diameter backward	1.800647	1.855632	1.792439	1.856333
Expected error (%)	0.04	0.45	0.12	0.59

$$nominal\,ticks\,per\,meter = \frac{nominal\,ticks\,per\,revolution}{nominal\,diameter \times \pi} \tag{6.1}$$

$$calibrated\,diameter = \frac{distance \times nominal\,ticks\,per\,meter}{measured\,ticks} \times nominal\,diameter \tag{6.2}$$

$$expected\,error = \frac{diameter\,(forward) - diameter\,(backward)}{2} \times 100 \tag{6.3}$$

6.2 Loop completion

Loop completion, or closed loop testing, is a method were the vehicle is driven from a known fixed position along some route, finally ending back in the same position and orientation. It is a very simple method, and comparing results between test runs is easy. The fixed point can be, for example, marked with physical objects, or just by painting the position in the ground. The testing is executed by starting from the fixed position and driving the vehicle along any route that will eventually end in the same position. There are two different ways to use this method. The first one is were the vehicle is always manually driven to the same exact marked position, and then checking the position given by the navigation system. In an ideal situation, the reported position should always be the same, but in reality, there will be differences. These differences can now be compared with the requirements or agreed limits and verify that they are small enough. The second alternative is to have the vehicle drive the loop to the same coordinates given by the navigation software, and then measuring the difference from the marked position by a tape measure. This alternative requires physically measuring the distances in the field, and being able to auto-drive.

A major benefit of loop completion is that it is easy to set up, since marking the fixed position in the field should not be a large task. Also, it is very flexible since the fixed position can be easily changed, and we can have multiple of them. Additionally, it allows any arbitrary route to be driven making it a very flexible testing method since were not limited to certain driving maneuvers such as in straight line driving. However, it suffers from one obvious weakness, loop completion does not acknowledge anything that happens during the driving outside of the fixed position. There is a possibility that navigation fails to function properly during the driving maneuvers, but eventually ends in the correct position. Therefore, there has to exist other testing methods that verify what is happening when the vehicle is driving outside of the fixed point.

6.3 Absolute measurement tracking

Absolute measurement tracking is a remarkably efficient method of verifying the correctness of the navigation system or odometry. The method allows locating small errors in the navigation and fine-tuning its parameters. It works by recording absolute measurements received from an absolute measurement sensor and then analysing those measurements over a long period. For example, it is used to manually and automatically calibrate wheel diameters, and to find optimal values for several navigation parameters. An example of parameter finding using absolute measurement tracking is given in subsection 6.3.1.

In this project, only marker detection sensors are used in absolute measurement tracking, since the satellite navigation receiver was deemed to be not accurate enough. The absolute measurement received from the sensor is compared with the current known position and, then converted to the difference between those positions. This difference is called a *position correction* and it is recorded for later analysis. A correction consists of longitudinal, lateral, and heading corrections. In an optimal situation, all of the corrections should always be zero, but since that is not the case, we can track how large the corrections are. Smaller corrections indicate accurate relative navigation and larger corrections indicate that there are errors in the navigation. Especially, if the corrections are mostly concentrated in the same direction, there is a bias in the relative navigation.

While a position correction consists only of three values, several values are derived from those for the analysis. Longitudinal and lateral corrections are recorded in the coordinates of the vehicle. Average and median values are also calculated. However, the most important values are the cumulative sums of the corrections. These sums tell us how the navigation is functioning over a long period. Even small biases are easy to detect by analyzing the cumulative sums.

As an example, let us consider a situation where the wheel diameters are estimated to be slightly larger than they really are. This would mean that the odometry estimates the distance travelled by the vehicle to be longer than the actual travel. If the error is large, it can easily be noticed, and will most likely prevent the navigation from working. However, if the error is small, it might not even have an effect on the navigation as other sensors can mitigate it. Absolute measurement tracking is a good method of finding such errors. Since the odometry reports a longer distance, the absolute measurements will correct that error by correcting the position of the vehicle backwards on most of the measurements. Now, if the vehicle is driven for a long period, and we keep recording the absolute measurements, we can track their progress. Even though the corrections are small, over a long period the sum of the longitudinal corrections will start to wander away from zero. Figure 6.1 shows and an example of using absolute measurement tracking to estimate the average wheel radius. It contains the estimated wheel radius from an original test run where the radius was set to a correct value. The other plot shows the radius in the same test run with an added initial error of 1 centimeter. The estimator quickly notices the incorrect wheel radius, and it is corrected back to the same original wheel radius. Figure 6.2 shows how the cumulative longitudinal corrections behaved with the same test run. Since the radius was estimated to be larger then it really was, the corrections where mostly positive and the sum increased quite a lot compared to the sum of corrections with the correct wheel radius.

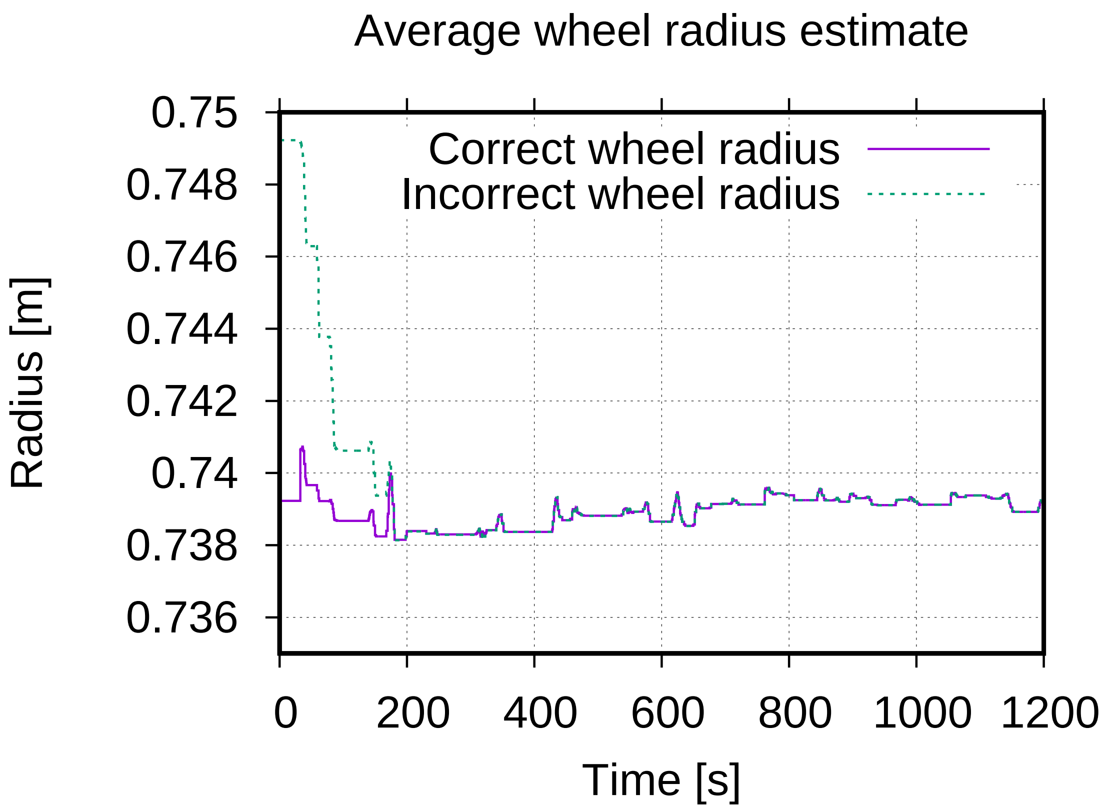

Figure 6.1 *Wheel radius estimation using absolute measurement tracking*

For another example, let us assume that the navigation estimates the turning of the vehicle to be marginally more than it should, i.e. the navigation system thinks that the vehicle is turning more than it really does. The error is small enough that the position stays accurate enough, and the vehicle is able to operate, because the absolute measurements correct the position. Now, if we track the sum of the lateral corrections it will start to wander away from zero, since the corrections are constantly correcting the position towards the outside of the curve.

6.3.1 Finding optimal value for cornering stiffness

Cornering stiffness coefficient, denoted by C_α [31], is an important parameter of a rubber tire. It is defined as the connection between the wheel slip angle of the

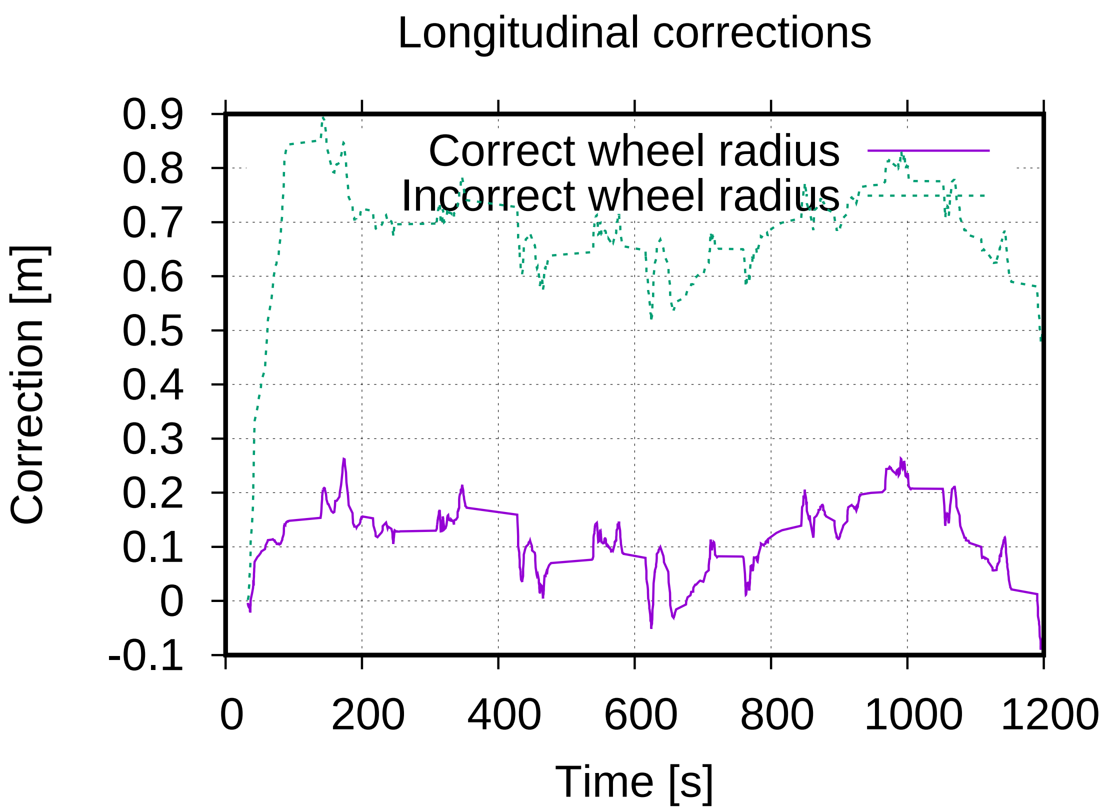

Figure 6.2 *Longitudinal position corrections with incorrect wheel radius*

tire and the lateral force applied to the tire. Wheel slip angle is the angle between the direction the tire is pointing and the actual direction where the wheel is going. Not taking it into account can greatly decrease the effectiveness of a navigation system [32]. These are illustrated in in Figure 6.3. Equation 6.4 is a model of the relationship between slip angle and lateral force.

$$F_y = C_\alpha F_z \tan\alpha, \tag{6.4}$$

where F_y is the lateral force applied by the tyre to the ground, C_α is the cornering stiffness coefficient, F_z is the vertical force applied by the tyre to the ground and α is the wheel slip angle. When the cornering stiffness coefficient C_α is multiplied with the vertical force F_z we get cornering stiffness for the given vertical force.

Originally, the navigation system at hand assumed a constant value for the cornering

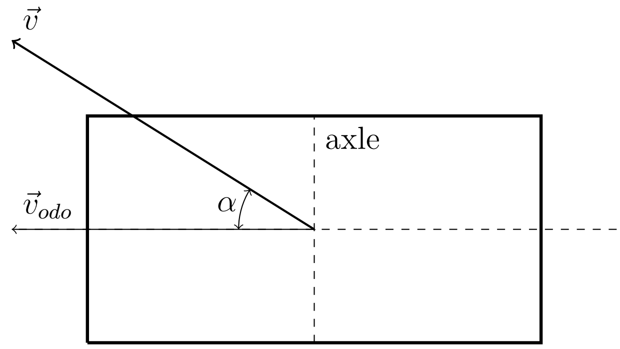

Figure 6.3 *Wheel slip angle, top view*

stiffness coefficient C_α, which was configurable for every wheel model. The parameter was configured and determined based on test runs performed without having maximum vertical load. Later, once the vehicle was driven with maximum vertical load, in certain situations, the navigation system was unable to operate. Inspection revealed a problem when the vehicle was turning, which was identified to be caused by an incorrect cornering stiffness coefficient. The vehicle was not turning correctly, making the odometry error so large that the rest of the sensors, mainly marker detection sensors, were unable to correct the position. The log files gathered from the incident were replayed with different cornering stiffness coefficients until optimal value was found. The original cornering stiffness value for the maximum load was $474577N$. After multiple calibration runs the final value for the parameter was estimated to be $189831N$. Total error in the cornering stiffness was almost 150% at maximum load.

The cornering stiffness coefficient finding was done by a combination of replaying real data and absolute measurement tracking. First, several test runs were executed with a full size vehicle with different vertical loads. Log files were then gathered from those for analysis. The analysis part consisted of replaying each log with multiple cornering stiffness coefficient values and then using absolute measurement tracking to identify the best value for the coefficient. The best value was chosen as the one that produces the smallest position corrections over a long period. These data points showed that the original assumption of the linear cornering stiffness model was not sufficient, as no linear slope fit the measured data with reasonable accuracy.

Table 6.2 shows how much the absolute measurements improve with the new cornering stiffness model. Since the cornering stiffness affects only the turning of the vehicle, there is no notable difference in the absolute sum of the longitudinal corrections. Sum of the lateral corrections in the other hand is a lot better than the original linear model. Also the sum of the heading corrections is better. The navigation system is also capable of making more position corrections, 1655 versus 1641, with the new model as a result of better odometry. The table represents only the results with maximum vertical load, but other loads had similar results so they were omitted from the table. Figures 6.4 and 6.5 show the progress of the longitudinal and lateral absolute correction sums with the original and new model.

Table 6.2 *Cornering stiffness estimation with maximum vertical load*

Absolute measurement tracking results	Original model	New model
Total corrections made	1641	1655
Absolute sum of longitudinal corrections	7.31 m	7.31 m
Absolute sum of lateral corrections	16.42 m	9.99 m
Absolute sum of heading corrections	2.29 rad	1.40 rad

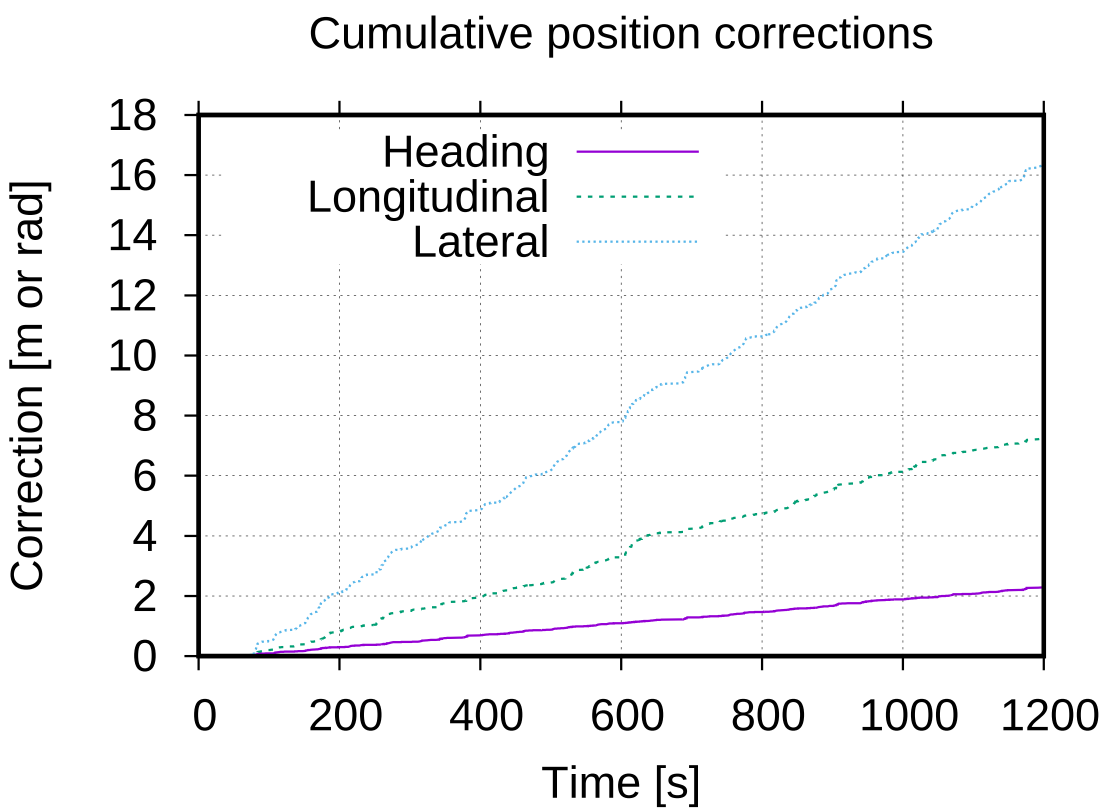

Figure 6.4 *Absolute measurement tracking with original cornering stiffness model*

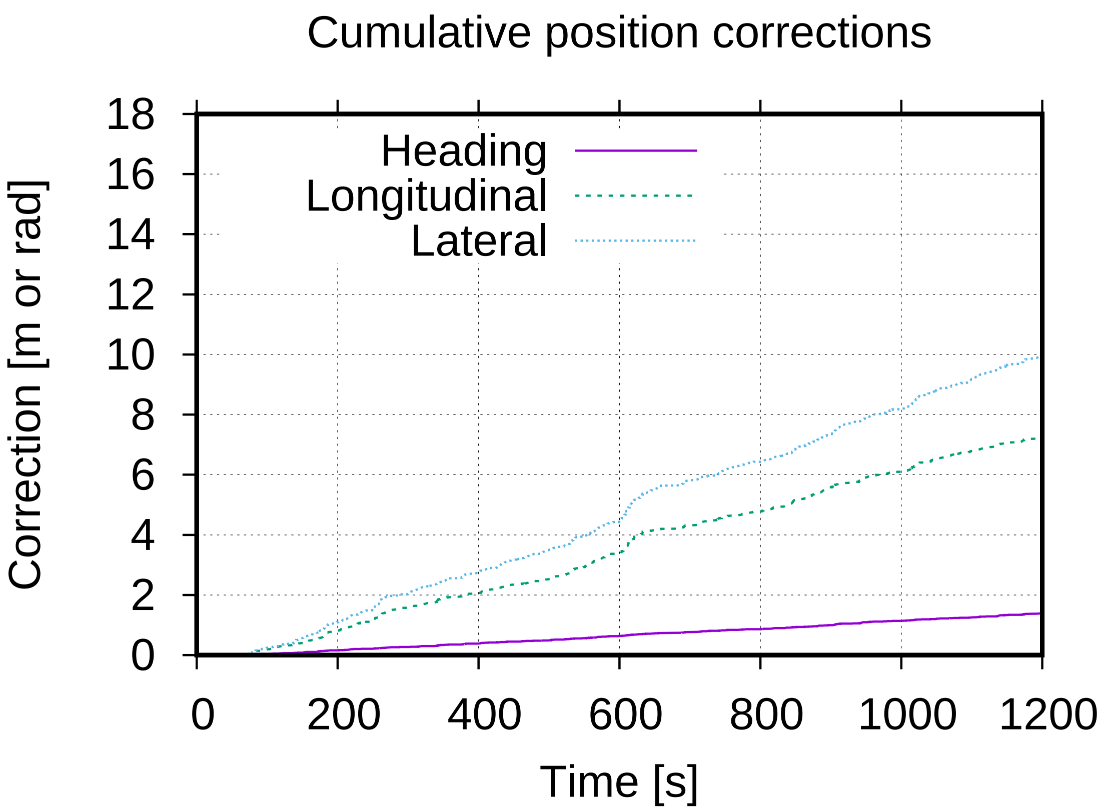

Figure 6.5 *Absolute measurement tracking with new cornering stiffness model*

Once enough data points were obtained using the data replay and absolute measurement tracking, it was obvious that a more complex model was needed to replace the original linear model. Polynomial interpolation was chosen, and second-, third-, and fourth-degree polynomials were fitted to the data points. A third-degree polynomial provided the best fit. Polynomial fitting was done using a program called *octave* and its function called *polyfit* [5]. Figure 6.6 shows the original linear model, the new polynomial model and the data points used in the polynomial interpolation.

6.4 Comparison to an existing system

Since the goal of the project is to replace an existing navigation system, we have the luxury of comparing the old and the new system. Two different methods can be used when comparing the systems. In the first method, the vehicle is driven with the old navigation system and log files are gathered. Those files are then converted to a format suitable for the new system. Since the new system supports

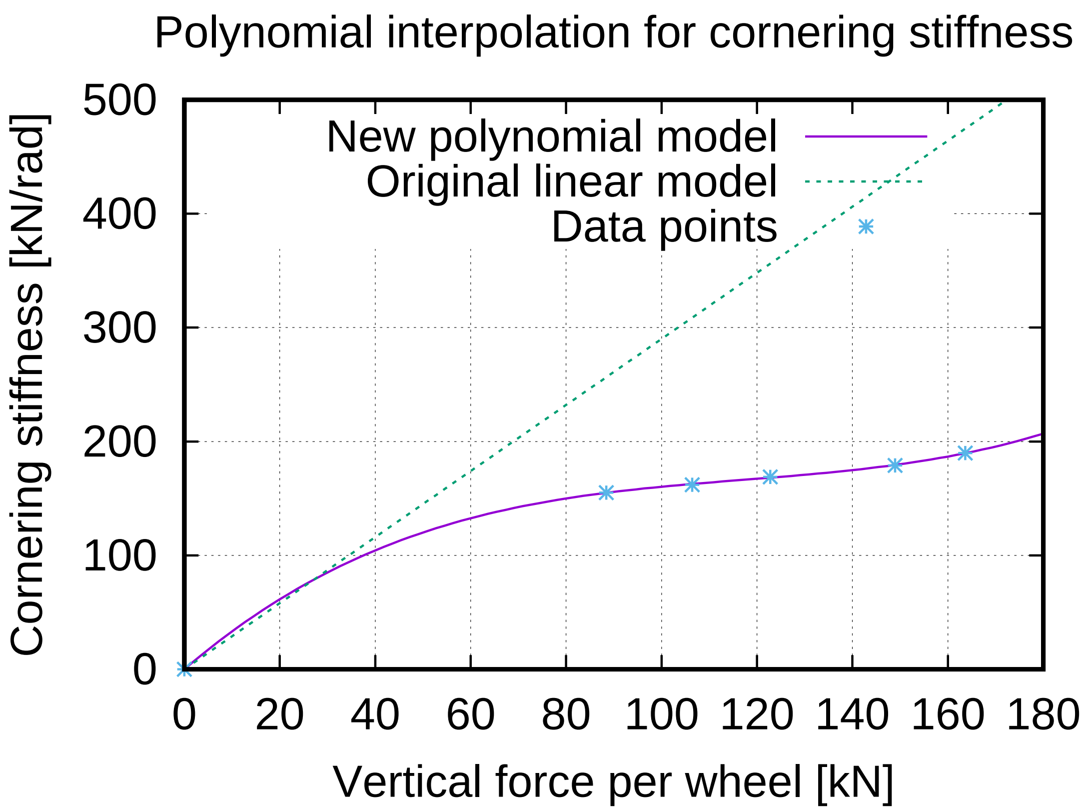

Figure 6.6 *Polynomial interpolation for cornering stiffness*

data replay, we can replay the same sensor data for the new system in order to obtain the corresponding navigation result from it. Now that we have one navigation result from the original test run with the old system, and another one from the log replay with the new system, we can compare them. The second alternative is to have both of the navigation systems installed in the same vehicle and have them navigate simultaneously. This way there is no need to replay log files later or do any conversion between log files. However, some potential problems might arrive having both systems run in the same vehicle. For example, the on-board computer might not be powerful enough to run both systems, or some sensors can not be used by more than one software at the same time. Additionally, the result from the GNSS receiver is used as a third reference in the comparison process.

The comparison itself consists of a two-part analysis. In the first part, the actual positions of both of the system are compared. This includes comparing longitudinal, lateral, and heading differences and possible timing differences. The second part compares the absolute measurements done by both of the systems.

Figure 6.7 shows a trajectory plot of straight-line driving between the new and the old system. Note the small x-axis scale compared with the y-axis. A trajectory plot is a good way to notice significant differences or biases quickly. An alternative to the trajectory plot is to plot the x- and y-coordinates separately as a function of time, in order to show any errors in timing. The position might be exactly the same for both systems based on the trajectory plot, but the position for the other system might have a significant delay.

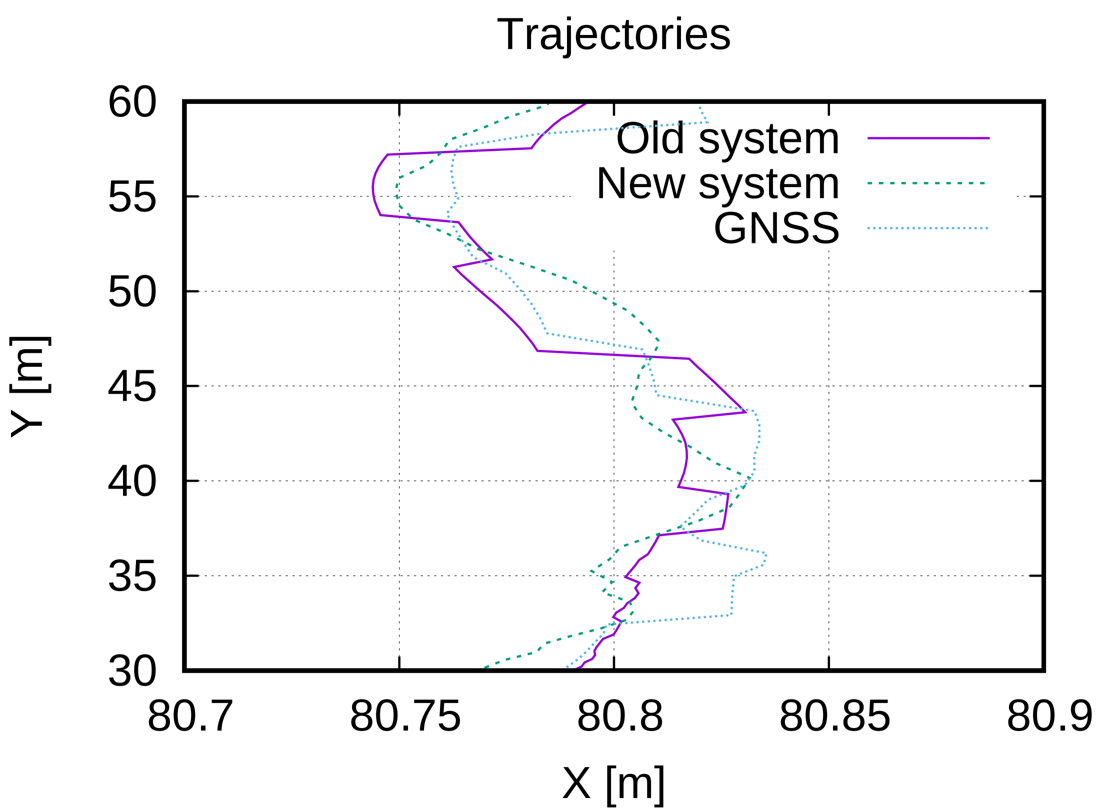

Figure 6.7 *Trajectories, x-axis magnified*

Figure 6.8 shows the absolute difference in position between the old and the new system. Heading is not taken into account in the difference. For a more detailed analysis, we can plot the longitudinal and lateral differences separately, and see if the difference is concentrated only on one of them. These are shown in Figure 6.9.

Table 6.3 shows the position correction results from an analysis between the old and

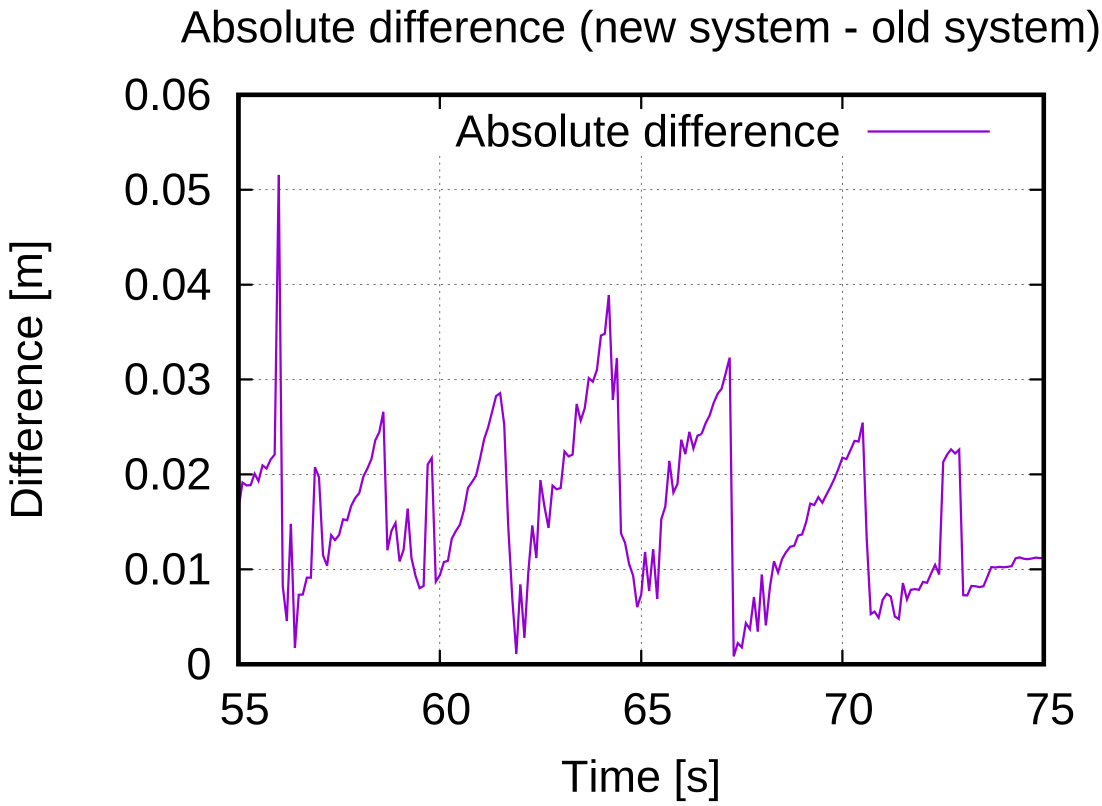

Figure 6.8 *Absolute difference*

the new system. The results were gathered by driving a vehicle with the old system and collection data. That data was then fed to the new system in order to obtain navigation results from it. Then the position corrections made by the two system were compared. The table shows that the new system operates much better in every comparison. It was even able to make one correction more than the old system. The analysis shows that the new system has a more accurate relative navigation as it makes smaller position corrections than the old system.

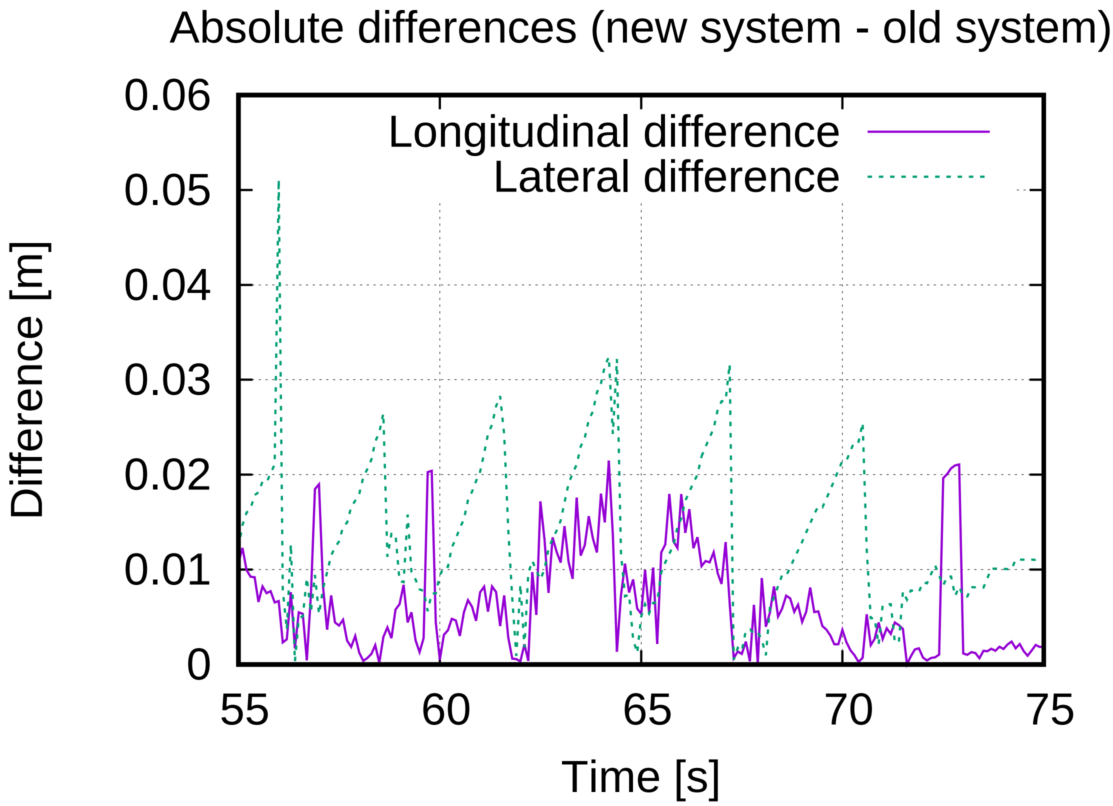

Figure 6.9 *Longitudinal and lateral differences*

Table 6.3 *Position corrections comparison*

	Old system	**New system**
Total corrections made	101	102
Maximum longitudinal correction	0.0465 m	0.0181 m
Maximum lateral correction	0.1359 m	0.0609 m
Maximum heading correction	0.0157 rad	0.0056 rad
Absolute sum of longitudinal corrections	0.3075 m	0.2151 m
Absolute sum of lateral corrections	0.7429 m	0.4394 m
Absolute sum of heading corrections	0.0972 rad	0.0441 rad

7. CONCLUSION

This thesis introduced platforms and methods on how to establish efficient verification process for a vehicle navigation system. Besides the platforms and methods, also a few examples were given, on how the verification and testing can be performed. During the project, an industrial vehicle navigation system was successfully developed and put to production use. The platforms and methods used in the development proved to be adequate for the verification process. The navigation system reached accuracy and robustness that met the requirements and autonomous operation of the vehicles was successful.

The platforms included simulation, a small indoor testing vehicle, and full size vehicles. The simulation software was capable of both an actual simulation and replaying real sensor data gathered from a physical vehicle. The simulation and data replay provided a fast and controllable platform for navigation development, testing and verification. They allowed multiple developers to test the navigation instantly on their own computers without having to rely on physical vehicles. Additionally, a controllable simulation is an excellent platform since the user can control the errors and there do not exist any unknown variables that might affect the navigation.

A small indoor testing vehicle provides a low-cost entry to the physical vehicles. It allows testing with real sensors in an actual vehicle that can still be driven inside the office. This makes rapid and inexpensive testing using a physical vehicle possible. In addition, testing with a small indoor vehicle first is a lot safer than going straight to a full size vehicle. The full size vehicle is the final and only complete testing platform. All of the other platforms can not accurately represent it, so for the verification to be complete, it is necessary.

The methods discussed were straight line driving, loop completion, absolute measurement tracking, and comparison to an existing system. Straight line driving acted as initial sanity check and a manual wheel encoder calibration method. It was very useful in the early parts of the development. It is vital for the system to be able to drive in a straight line before cornering should be even addressed. Loop completion is a very simple method that is easy to execute and does not require anything from the navigation system. It can be used to verify the repeatability of the system over any arbitrary route. Absolute measurement tracking proved to be the most versatile verification method used in the project. It is easy to implement but can be used for almost anything. Examples include automatic wheel diameter estimation during operation, verifying the accuracy of the relative navigation, and finding optimal values for several navigation parameters.

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